How can FPSO units be efficiently protected from falling objects on offshore installations?



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Preface

This document serves as a report of the research I have conducted on dropped object protection structures on FPSO units. The research on this subject was done in collaboration with SBM Offshore, where I had the pleasure of doing a two-month internship. This research was done for the subject CTB3000-16 Bachelor Eindwerk, which is part of the bachelor Civil Engineering at the TU Delft.

Finally, I want to thank my supervisor at the TU Delft, Dr.ir. P.C.J. Hoogenboom and T.R. van Woudenberg MSc, and at SBM Offshore, Timo de Beer and Hristinka Dimitrova for their guidance and feedback during this research project.

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Note on the use of AI:
AI has been used in this report to check language, spelling and grammar. AI was also used to double-check calculations to avoid mistakes. For these actions, Microsoft Copilot has been used. For spelling and grammar, Grammarly has also been used. AI has not been used to generate content whatsoever.

Summary

During the production of oil on FPSO units, accidents can always happen. One type of accident that happens on FPSO units is the dropping of objects during lifting. The dropping of objects can cause damage to installations and pose a risk to the safety of personnel. To prevent these consequences, dropped object protection structures (DOPS) are installed on FPSO units. This report answers the following research question: 'How can Dropped Object Protection Structures (DOPS) be efficiently designed for use on Floating Production Storage and Offloading (FPSO) units?'. This research question is answered by designing DOPS for an FPSO unit of SBM Offshore.

The goal of any DOPS is to protect whatever lies underneath from the impact of dropped objects. The absorption of the largest impact loads is done with the use of plastic deformation of steel. For the design of DOPS, it is of great importance that the design is economically feasible, which is why a risk analysis is needed to see what is still feasible for a DOPS to withstand.

Based on the risk analysis done in this report, the impact load of 294.3 kJ at both the Auxiliary Laydown (TS003) and Main Laydown 1 (TS151) is the highest load that is still within economic feasibility. The actual worst-case scenario load would be 706.32 kJ, but this had a way lower chance of occurring.

To model the impact, first an elastic model was considered. It turned out this model was insufficient for the largest impact loads, because it generated an unrealistically high force. After that, a plastic model was used to model impact using plastic hinges. This model better encapsulated the absorption of the impact load and calculated a more realistic generated force. This model incorporated the following failure mechanisms to see if the DOPS is structurally sound:

- Fracture due to excessive bending in the beam
- Buckling of the columns
- Plate buckling of the beam
- Lateral torsion buckling of the beam (LTB)

After the plastic model was set up, three different design variants were considered and tested based on the model. The following variants were tested:

- Variant 1: HE cross-section beams welded to a HE cross-section beam connected to HE columns.
- Variant 2: IPE cross-section beams welded to an IPE cross-section connected to RHS columns.
- Variant 3: A steel plate welded to the top of an RHS cross-section beam connected to HEA columns.

Testing the different variants showed that HEB beams performed best at absorbing the impact load. The RHS profiles also showed potential but less so than the HEB beams. IPE profiles were deemed unfit for use in DOPS due to vulnerability to plate buckling and LTB. For the columns, the square RHS profiles performed the best due to them having no weak axis.

Based on these results from the variant, a final design was made with HEB 320 beams and RHS 300x300x6.3 columns. This final variant was tested using a FEM analysis to see how the results compared to the plastic model. The results differed due to inaccurate assumptions made in the plastic model. Iterating upon these values already showed results that were more similar between the model and the FEM analysis. More fine-tuning of the assumptions could make for a more accurate model. For the design of the DOPS, the model can be used but in combination with a FEM analysis to get a better understanding of how the impact load will be absorbed.

In the discussion, more topics were highlighted that were left out of this research ore under researched. They could be of importance and could thus be further researched. The following topics were discussed.

- Effect of stiffer steel
- Influence of shear force
- HEB vs RHS
- Assumptions and factors in plastic model

In the conclusion, it was concluded that the design process should start with a risk analysis so that it can be used to get the design impact load. For the beam, the HEB cross section performs the best, but it does need stiffeners to prevent plate buckling and LTB, which were brought to light with the FEM analysis. For the column, the square RHS cross sections are best. For the load path, a simple structure turned out to be the most efficient. The connections of the structure should be over-dimensioned to avoid plastic deformations in those parts of the structure.

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1 Introduction

Floating Production Storage and Offloading (FPSO) units play a significant role in the production of oil on offshore installations. One of these massive vessels can produce up to 250 000 barrels a day (SBM Offshore, z.d.). The extraction of oil and gas on these FPSO units is a dynamic process because of the live production happening on these vessels. With this dynamic process comes the risk of objects falling and damaging production equipment or worse. To combat this risk, so-called Dropped Object Protection Structures (DOPS) are installed on FPSO units to protect the installations. DOPS serve to protect the installations and technical equipment on FPSO units by sheltering them from the impact of dropped objects (SBM Offshore, 2026).

Dropped object protection structures are an important part of FPSO units because they allow for the safe production of oil on these vessels. It is thus of great importance that DOPS are effective and efficiently designed to ensure a smooth process on FPSO units, which is integral for the production of oil on offshore installations.

The challenge with designing DOPS comes from identifying the impacts and loads these structures need to absorb and adequately designing a structure that can take in these loads. When the DOPS are under-dimensioned, the risk of damage to the installations can occur and when over-dimensioned, important resources like steel are wasted. It can thus be a problem to find a good balance because of the uncertainty dropped objects give.

This report serves to answer the following research question: 'How can Dropped Object Protection Structures (DOPS) be efficiently designed for use on Floating Production Storage and Offloading (FPSO) units?' This research question will be answered by designing a DOPS for the FPSO units of the offshore company SBM Offshore. This design process will offer insight into the way DOPS are designed and how their design can be optimised.

The content of this report is as follows. Chapter 2 will explain the method of research used to answer the research question. Chapter 3 will explain the goal and design requirements of a DOPS. Chapter 4 will research what areas of the FPSO are at risk of dropped objects and what objects will cause the worst-case scenario within these areas. Chapter 5 will discuss how the impact of these dropped objects can be modelled and how this can be used for further calculations. In Chapter 6, multiple concepts will be designed and compared with each other. Chapter 7 will further iterate on the best design of Chapter 6 and perform a FEM analysis. In Chapter 8, there is room for discussion about the research and what could be further researched, and finally, in Chapter 9, there will be a conclusion about DOPS and design recommendations.

2 Method of research

The research question will be answered by designing a DOPS for an FPSO unit and reflecting on this process to see how the design can be optimised and streamlined. Based on this process, suggestions and recommendations will be given about the best design options for DOPS.

The design process will start by looking at what the goal of a DOPS is and what methods can be used to achieve this goal. This is followed by design requirements that the DOPS should have.

The design process will continue by analysing which objects are at risk of falling at what place on the FPSO unit. Based on this, impact loads can be calculated, which are crucial for designing the DOPS. The necessary information will be gained from research papers by SBM Offshore about the designs of FPSO units.

With this information, the research will continue with setting up a model that can model the impact of the dropped object on the structure. The goal of this model is to calculate a generated force and look at the deformations of the structure. In the model, multiple failure mechanisms will be included to research how the structure could fail.

Based on the impact loads, multiple design concepts for the DOPS will be made. The different design concepts will test different cross-sections and structural layouts. The different concepts will be tested using the model. The best evaluated concepts will be further worked out into a final design to see what is necessary to complete the design of a DOPS for a FPSO unit.

All this will lead to a report which includes the following:

- Dropped objects risk and impact analysis
- Model of dropped objects impact for DOPS
- Multiple design concepts
- Optimisation of best design concept for the DOPS
- FEM analysis of final design concept
- Design recommendations and advice based on the design process in this report

3 Goal and design requirements for a DOPS

The goal of any Dropped Object Protection Structure is to protect whatever lies underneath from the danger of falling objects. This chapter will mention the goal and design requirements around which a DOPS needs to be designed to achieve an economic design.

3.1 DOPS goal and methods of achieving it

The primary goal of a dropped object protection structure in the context of an FPSO unit is to limit damage and avoid accidents caused by dropped objects. A DOPS does this by absorbing the impact energy of falling objects. The primary way DOPS absorb this impact energy is through the deformation of steel. For objects with a low impact energy, elastic deformation suffices, but for larger objects with a high impact energy, plastic deformation is needed. This plastic deformation is needed to absorb energy in an economic and safe way, because only elastic deformation would require large cross-sections and could redirect objects in unwanted directions.

The absorption of energy and plastic deformation of the DOPS can be handled in different methods. Ways DOPS can plastically deform are through the bending of steel beams, the deformations of steel plates, and the compression of steel columns. Plastic deformation will be accounted for by using a crumble zone, which indicates what part of the DOPS is allowed to plastically deform.

The nature of a DOPS is to sacrifice its parts to protect whatever lies underneath. This means tolerable deformations and damage differ a lot from regular construction. The goal of a DOPS is not reached when the steel components of the structure fail and thus fail at protecting the underlying installations. The DOPS will therefore be tested to determine whether structural failure is avoided and, with that, keep the goal alive.

Being economically logical is also of great importance for a DOPS because designing a structure that costs more than the objects it is protecting would be illogical. A risk analysis is thus an important part of the design process to come to an economically sound design.

3.2 Design requirements

For the design of the DOPS, the following boundary conditions will be applied:

- Design for the DOPS will be a 3D portal frame with fixed supports to the FPSO unit
- The design of the DOPS is modular, so it can be adapted and placed on different parts of the FPSO to protect all sorts of installations.
- The design span will be 5800 mm, the same as the c.t.c. distance of the FPSO unit (this can be changed when smaller objects need to be protected).
- The design needs to be optimal, so the structure remains light, and no resources are wasted.
- The design will need to stay within economic logic.
- The DOPS will need to experience controlled plastic deformation for the higher impact loads to be able to absorb the impact energy.
- The serviceability limit state can be reached, but fracture of steel components is not allowed.
- The crumble zone needs to be sufficient to avoid collision of the DOPS with underlying installations.
- The components of the DOPS need to be demountable so they can be repaired or replaced when damaged.

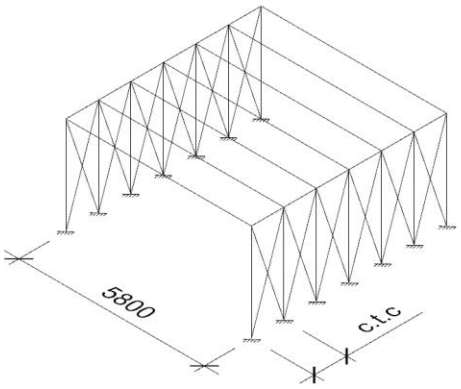

Figure 3-1: 3D free body diagram of basic DOPS

4 Areas and objects at risk

This chapter will focus on the areas and installations on the FPSO units that are at risk of dropped objects. For these areas, the mass and dropped height of the dropped objects will be analysed. With this data, calculations will be made for the impact energy of the dropped objects. This will all lead to a comprehensive risk analysis for the dropped objects, which will give a design load that is economically feasible.

4.1 Areas on FPSO units

On FPSO units, multiple cranes are stationed to move around objects. These cranes operate around different parts of the FPSO unit and put different installations of the FPSO at risk of falling objects.

The modern-day FPSO units are home to two different cranes located near the front and back of the FPSO unit. The 'primary Starboard crane' is of the knuckle-boom type and is located towards the back of the vessel, and the 'secondary starboard crane' is of the fixed-boom type and is located more towards the front of the vessel. The two cranes both have different reach and weight capacities. The reach and weight also differ for inboard and outboard loading. The relevant reaches and lifting capacities can be found in Table 4-1.

Table 4-1: Overview of reach and carrying capacity cranes FPSO Unit, based on information from SBM Offshore

Primary Starboard Crane	**Secondary Starboard Crane**
1. Outboard: 40 tons at 20 metres reach	1. Outboard: 15 tons at 35 metres reach
2. Outboard: 25 tons at 32 metres reach	2. Inboard: 15 tons at 35 metres reach
3. Inboard: 35 tons at 32 metres reach	

The reach and carrying capacity of only the main hoist of both cranes have been considered, because the carrying capacity and reach are the biggest. The reaches are used to look at the areas on the FPSO units that are in danger of falling objects. For the impact loads, the carrying capacity of the cranes won't be used. This is because, for the most efficient design, it is better to look at what the cranes are lifting to avoid the over-dimensioning of the DOPS. For the impact loads, the relevant dropped objects and their impact will be used within the module that is applicable.

Based on the reaches of the cranes, the following modules of the FPSO have been identified as being at risk of falling objects. For the Primary Starboard Crane, the following modules are at risk:

- Module TS032 - Power generator module 2
- Module TS151- Laydown main 1
- Module TS101 - Chemical injection module
- Module TS001 - Separation module 1
- Module TS003 - Separation module 3

For the Secondary Starboard Crane, the following modules are at risk:

- Module TS003 – Separation module 3
- Module TS002 – Separation module 2
- Module TS014 – Gas compression module 4
- Module TS015 – Gas compression module 5
- Module TS051 – Flare knockout drum

In Figure 4-1 the range of the cranes and where the different modules are located on the FPSO can be seen. The blue areas represent the areas that are at risk because of the primary crane, the green areas represent the areas that are at risk because of the secondary crane, and the teal area represents the area that is at risk of both cranes.

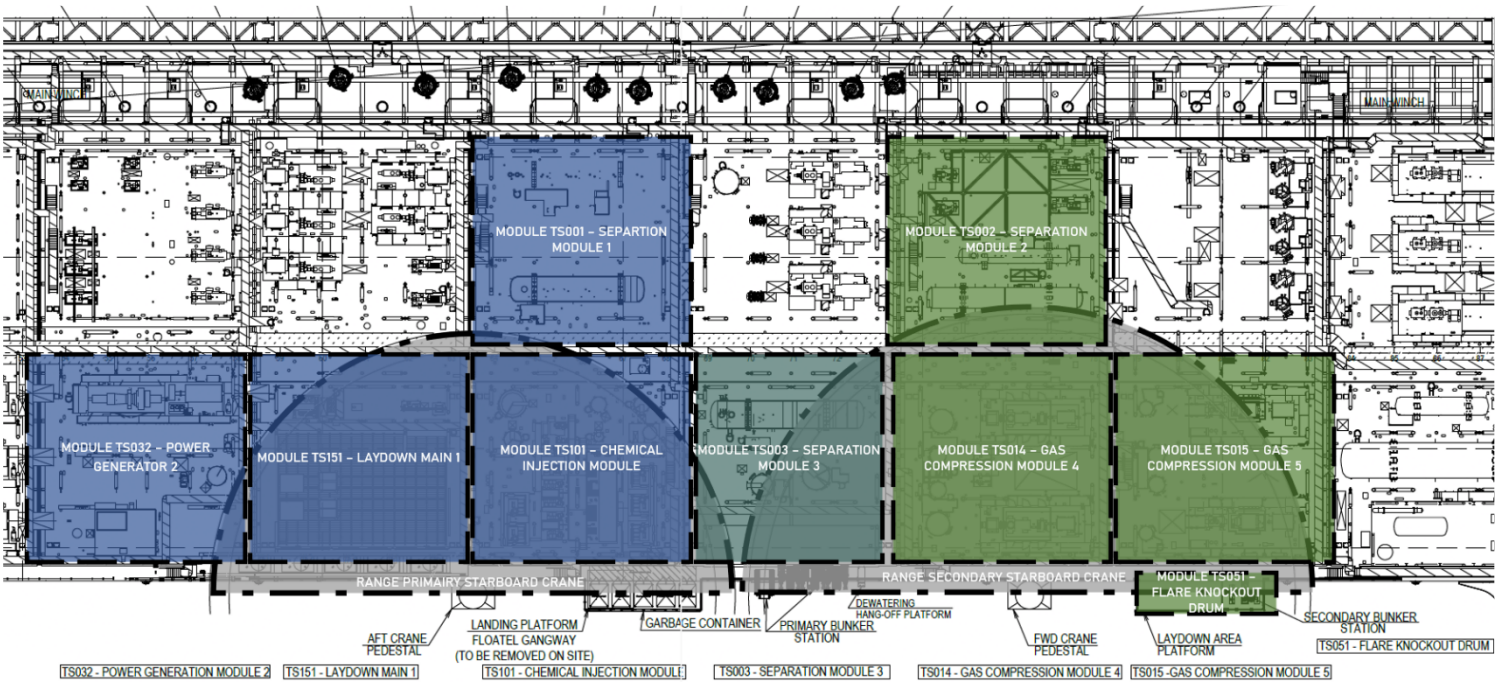

Figure 4-1: Overview of different modules that are at risk on the FPSO, the background is a typical layout of a modern FPSO provided by SBM Offshore

Within these modules, all different types of equipment and installations are at risk of dropped objects. According to information from SBM Offshore, the following laydown zones are at risk:

Due to the Primary Starboard Crane:

- The main laydown 1 area in module TS151
- The chemical laydown (Tote tank storage 2nd level) area in module TS101
- The garbage container laydown area next to module TS101
- The transition laydown area between module TS001 and TS101
- Pick-up point (tote tank storage 5th level) in module TS001

Due to the Secondary Starboard Crane:

- The auxiliary laydown area in Module TS003
- The deck (Forward) laydown area next to Module TS015
- Pick-up point in module TS003

In Figure 4-2 the laydown zones deemed at risk by SBM Offshore can be seen. These areas are the same as the ones seen in Figure 4-1 which was made based on the reach of the cranes. Two zones, TS014 and TS002, have been left out in Figure 4-2 based on the lifting route. The information from SBM Offshore gives a more streamlined view of what areas are at risk based on lifting routes. So, for the rest of this research, the areas highlighted in Figure 4-2 will be used to come to a more optimal design.

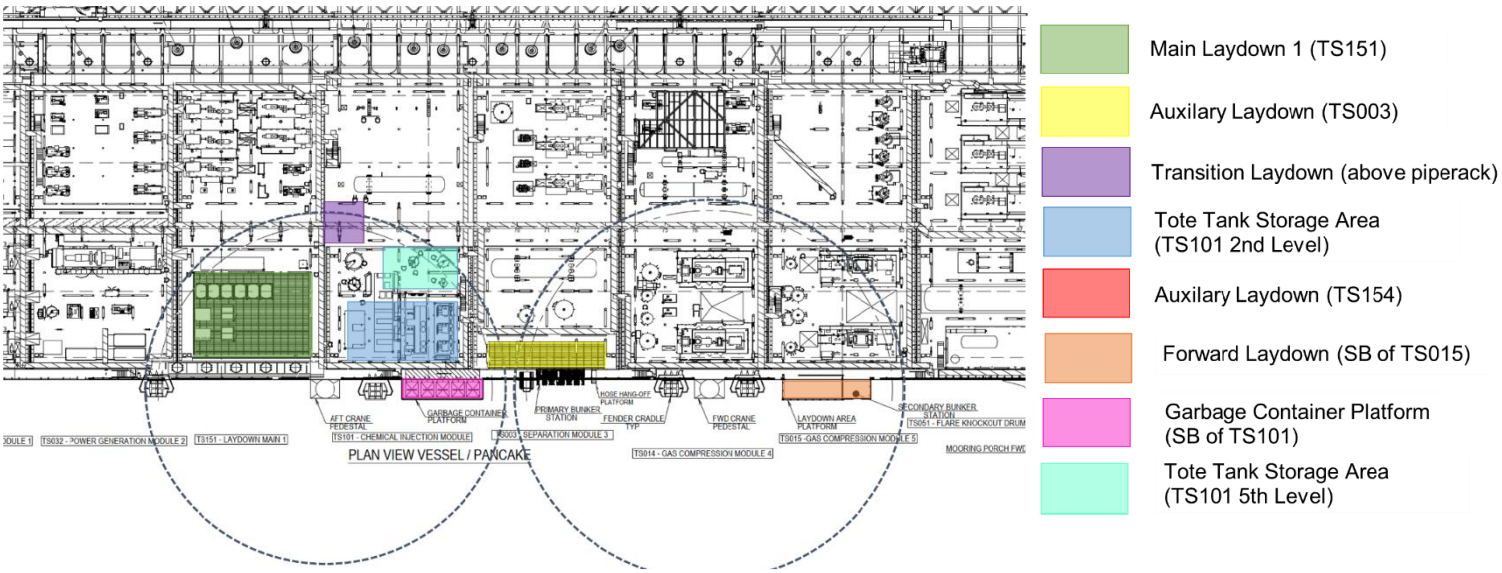

Figure 4-2: Vulnerable areas on the FPSO. This overview also contains the Auxilary Laydown TS154, which is outside the reach of the cranes and is located on the left outside of the figure. Typical FPSO layout from SBM Offshore

4.2 Dropped objects and their impact loads

Based on the relevant areas found in the previous section 4.1, the objects that are at risk of dropping will now be researched. For these objects, the mass and drop height will be determined. Based on the mass and drop height, the impact load will be calculated. This will be done by calculating the gravitational energy.

For the gravitational energy, the following formula will be used (Hibbler, 2022, p.197):

$$E_g = m * g * h \quad [J]$$

With: m [kg] : Mass of dropped object
g [m/s^2] : Gravitational Constant 9.81 m/s^2
h [m] : Height from which the object is dropped

According to the research conducted for SBM Offshore, the height of the dropped height of the critical objects is equal to 2 metres. The study says that for the heaviest objects, the lifting height is assumed to be 2 metres above the relevant installation. So, a dropped height of 2 metres will be used to calculate the relevant dropped impact energy. At this height, the potential effect of the drag force can be ignored, see the example in Appendix A.

The same report from SBM Offshore mentions that for containers the impact of a fall will be partially absorbed by deformation of the container. They estimated this to be 25% of the impact energy. To account for this, a shape factor α will be added to the formula of the gravitational energy.

$$E_g = m * g * h * \alpha \quad [J]$$

With: α [-] : shape factor, α = 0.75 for containers, otherwise α = 1

A list of the full calculations for all the impact energy of the dropped objects and their relevant laydown areas can be found in Appendix B. The objects that cause the critical impact load are presented in Table 4-2 below.

Table 4-2: Dropped Objects causing critical impact energy, source mass of object

Laydown Area	Object	Mass of object (kg)	Shape factor	Impact Energy (kJ)
Auxiliary Laydown TS003	Sludge Disposal Tanks - full	15000	1	294.3
Garbage Platform	Waste Skips (hazardous) - full	9750	0.75	143.47125
Main Laydown 1 TS151	Tote tanks/ chemicals (20m3) - full	36000	1	706.32

Tote Tank storage area TS101- level 2	Tote Tanks/ Chemicals (4.5m3) - full	5250	1	103.005
Tote Tank storage area TS101 – level 5	Tote Tanks/ Chemicals (4.5m3) - full	5250	1	103.005
Transition Laydown (above pipe rack)	Intelligent pigs from TS041	275	1	5.3955

Comparing the results of Table 4-2 to the Table 4-3 from SBM Offshore, the results are the same except for the following zones: Laydown 1 (TS151), Auxiliary Laydown TS003 and Tote Tank Storage Area (TS101) – level 5.

For the Main Laydown 1 (TS151) and Auxiliary Laydown (TS003), the loads identified in Table 4-2 are substantially bigger than the ones given in Table 4-3 below. For Table 4-3 the second biggest load was taken. The difference in Tote Tank Storage Area (TS101) comes from the larger drop height in Table 4-3. For the worst-case scenario, the highest value for the impact energy will be considered from both Table 4-2 and Table 4-3.

Table 4-3: Table of impact energy, based on client sensitive information of SBM Offshore

Laydown / other targets	Total impact frequency /year	DAL impact energy (kJ)
Main Laydown 1 (TS151)	1.1E-02	294*
Heli-refuelling Storage/ Pump Unit	2.5E-03	36*
Desanding Degasser Skid Package		
Desanding Filter & Desander Cyclone		
Seawater lift pumps (dropped object protection)	1.1E-02	294*
Seawater lift pump discharge pipe Note 2	1.1E-02	294*
Auxiliary Laydown (TS003)	2.4E-03	147
Transition Laydown (above piperack)	5.3E-03	5*
Piperack	2.5E-03	19*
Tote Tank Storage Area (TS101) - Level 2	1.1E-02	103*
Tote Tank Storage Area (TS101) – Level 5	3.6E-02	103*
Level 2 TS101 Area Note 3	3.6E-02	711*
Garbage Container Platform	2.4E-03	143*
Auxiliary Laydown (TS154)	7.6E-04	121*
B-deck laydown	7.6E-04	44*
Main Deck (under monorail beam)	6.6E-04	243*
Firewater Ringmain (under monorail beam)	6.6E-04	177*

Note: An asterisk (*) indicates that the drop / swing frequency of the object with the highest impact energy exceeds 1E-04 per year.

Note 2: Although the DAL calculation in Section 6.1.1.1 suggests an impact energy of 1,695 kJ would be required to protect this target, it is assumed that any protection implemented would be an extension of the dropped object protection above the seawater lift pumps and therefore the maximum lift height would be 2 m above this protection.

Note 3: Lifts passing over tote tank storage area Level 2 enroute to tote tank storage area Level 5 at a height of 13.8m above Level 2.

The impact energy for the different laydown zones for the worst-case scenario is as follows:

- Auxiliary Laydown (TS003): 294.3 kJ
- Garbage Platform: 143.47125 kJ
- Main Laydown 1 (TS151): 706.32 kJ
- Tote Tank Storage Area TS101 – level 2: 711 kJ
- Tote Tank Storage Area TS101 – level 5: 103.005 kJ
- Transition Laydown: 5.3955 kJ

(The impact load of the Transition Laydown is insignificantly low when compared to the other zones, so it will be ignored)

4.3 Economic design impacts

The impact energy of the worst-case scenario of both the Main laydown 1 (TS151) and Tote Tank Storage Area (TS101) is extremely high. A structure that can withstand these impact loads will need very large cross-sections and will thus cost a lot and possibly waste resources. To come to a more economically viable and sustainable design, the risk of these scenarios needs to be studied.

The 'critical' dropped objects all have different probabilities when it comes to their occurrence. The risk was determined based on the impact load and the yearly occurrence, and this gives the following impact loads that will be used for further calculations.

- Auxiliary Laydown (TS003): 294.3 kJ - Yearly occurrence: $2.4*10^{-5}$ [-]
- Garbage Platform: 143.47125 kJ - Yearly occurrence: $4.9*10^{-4}$ [-]
- Main Laydown 1 (TS151): 294.3 kJ - Yearly occurrence: $2.2*10^{-4}$ [-]
- TS101 – level 2: 103.500 kJ - Yearly occurrence: $4.0*10^{-3}$ [-]
- TS101 – level 5: 103.005 kJ - Yearly occurrence: $4.3*10^{-3}$ [-]

The impact load 294.3 kJ at both the Auxiliary Laydown (TS003) and Main Laydown 1 (TS151) will be considered as the worst-case scenario, which is still economically sound. The worst-case scenario loads of more than 700 kJ were deemed economically unfeasible, because their chance of occurring was 10 times less likely than the 294.3 kJ at Main Laydown 1 (TS151).

5 Modelling of impact loads

This chapter will discuss how the impact of the dropped objects can be modelled, so the structural integrity of the DOPS can be calculated. After that, different failure mechanisms will be discussed to see which one will possibly cause failure of the structure.

The goal of this chapter is to find a model which can encapsulate the impact energy of the dropped object and model the forces and deformations of the DOPS.

5.1 Mass-spring system

The first method that will be discussed is the mass-spring system so deformations can be calculated. This model will only account for elastic deformation of the DOPS.

The relation between energy and force is as follows (Hibbler, 2022, p.200):

$$E = \int_{s_1}^{s_2} F * ds \qquad \text{[kJ]}$$

With F [N] : Force
s [m] : distance

For the context of this model, the distance s will be the distance the dropped object traverses from impact with the DOPS to a standstill. The assumption will be made that the force is constant over this distance, and this means that the integral can be removed, giving:

$$E_{impact} = F_{average} * s \qquad \text{[kJ]}$$

To gain the stopping distance of the dropped object, a mass-spring system will be used. To start with the model, a simplified model, consisting of a beam on two columns, will be used, for which the columns will be considered as springs and the beam as infinitely stiff. Modelling this gives the formula below (Derivation can be found in Appendix B)

$$F = \sqrt{\frac{4EA}{H} * E_{impact}} = \sqrt{\frac{4EA}{H} * m * g * h} \qquad \text{[N]}$$

With EA [N] : Young's modulus * area of cross-section of the column
H [m] : height of the Column

The model will now be further expanded to include the bending of the beam, this gives:

$$F = \sqrt{2 * E_{impact} * k_{system}} = \sqrt{\frac{2*m*g*h}{\frac{L^3}{48EI} + \frac{H}{2EA}}}$$

With EI [Nm^2] : Young's modulus * moment of inertia of beam
L [m] : length of beam

The free body diagram used for setting up this model can be seen in Figure 5-1 down below.

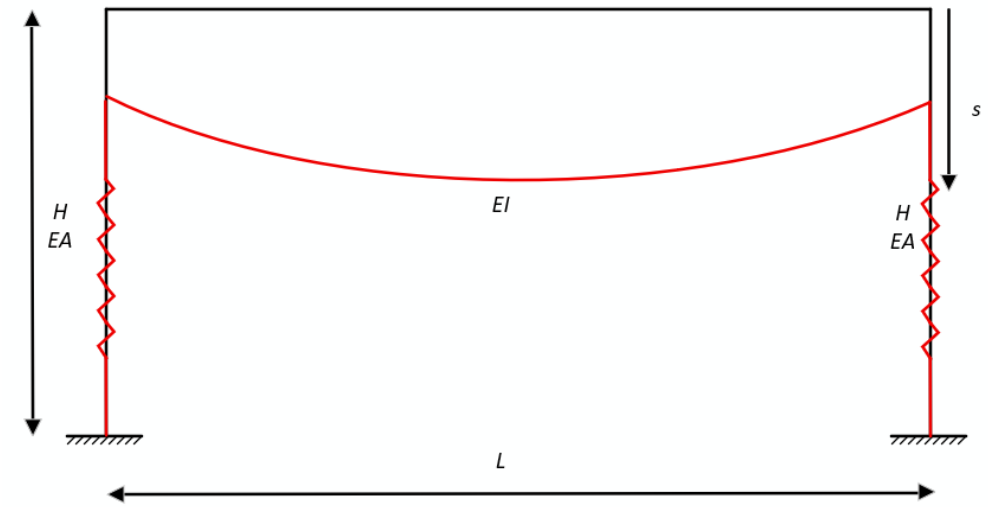

Figure 5-1: Portal for mass spring system

Using the elastic model to calculate the force will give a force in the order of mega Newton's for most steel profiles. See Appendix D for an example. This is an extremely large force, and it would thus be impossible for any normal-sized cross-section to absorb this force without plastic deformation.

Another problem with absorbing the force with elastic deformation is that this elastic property works both ways, and thus the DOPS could bounce the dropped object back, causing it to go in an unwanted direction. This could be dangerous and cause a lot of damage. Plastic deformation is thus needed to absorb the impact energy.

For heavier impact objects and impact loads, the elastic model will not suffice. For smaller objects, this model can still be used. This model still has some merit for these objects, which the DOPS also has to absorb and preferably without plastic deformation because that would require repairs.

5.2 Plastic deformation model

To account for the shortcomings of the elastic model discussed in the previous section, the model that will be discussed in this section is one that considers plastic deformation. For this model, a sacrificial height will be added to the DOPS, which can deform without the underlying installation being damaged. Based on this sacrificial height, the force generated by the impact energy can be calculated.

The average force generated by the impact energy will be calculated by using the relation between force and energy. The formula used can be seen below:

$$F = \frac{E}{s} \quad [\text{kN}]$$

With E [kJ] : Impact energy
s [m] : sacrificial height

Using the relation mentioned above only gives the average force, while the peak force will be larger than this. For an elastic relation, the peak force is 2x the average force. While for a fully plastic model, the peak force would be the same as the average force. While this model considers just plastic deformation, a factor of 1.5 will be taken to account for the reality that the beam will first elastically deform and then plastically deform. The peak force can be calculated using the following formula:

$$F = \frac{E}{s} * 1.5 \quad [\text{kN}]$$

This model will assume that the structure will turn into a mechanism to allow for plastic deformation. This will be modelled by adding plastic hinges into the beam. These plastic hinges will be used to further calculate what the internal and external forces of the DOPS will be. The mechanism can be seen below in Figure 5-2.

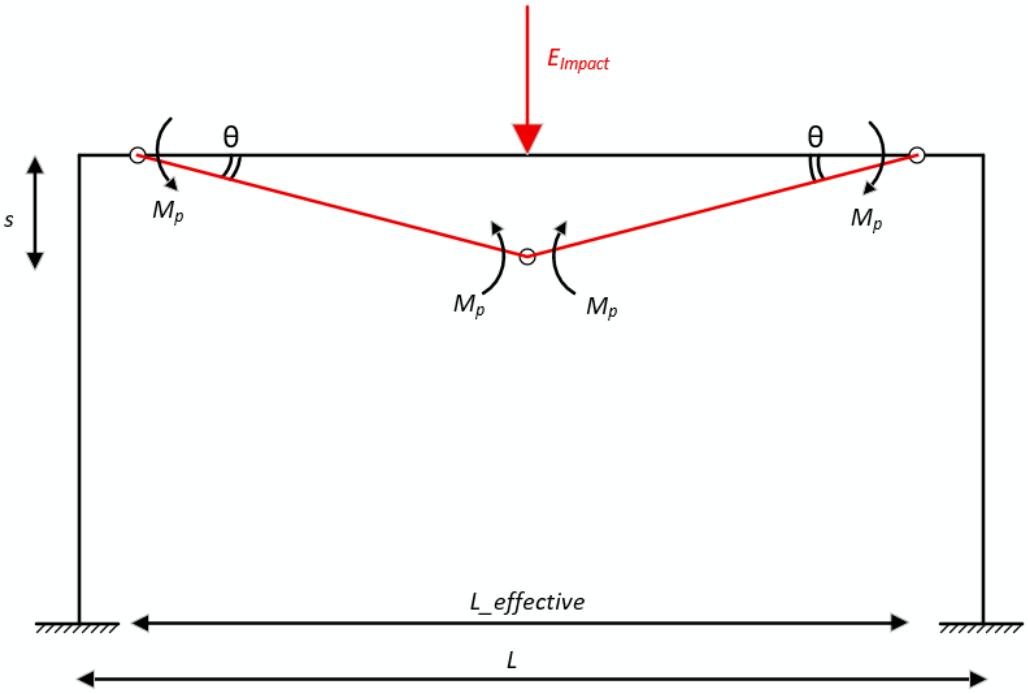

Figure 5-2: Mechanism of plastic hinges

The assumption will be made that all impact energy will be absorbed by the structure via plastic deformation and that the sum of all energy in the entire system will thus be equal to zero. This gives the following equation:

$$\sum \mathrm{E} = E_{impact} - E_{plastic} = 0$$

The mechanism that will form consists of three plastic hinges, one in the middle of the beam and two at the end of the beam near the connection. This mechanism can be seen in Figure 5-2. The mechanism gives the following expression:

$E_{impact} = 4 * M_{plastic} * \theta$ [kJ]

With $M_{plastic}$ [kNm] : Plastic moment capacity of cross-section
θ [rad] : Angle of hinge

With this derived expression, the angle θ can be calculated, which can then be used to calculate the displacement of the middle of the beam. With this displacement, the force generated can be calculated with the relation between force and energy. The plastic moment capacity will be calculated with the following formula:

$M_{plastic} = W_{y,elastic} * f_y * \alpha$ [kNm]

With: $W_{y,\,elastic}$ [m^3] : Elastic Section modulus
f_y [N/m^2] : Yield strength of steel
α [-] : Shape factor for cross-section

The forming of plastic hinges at the connection between column and beam should be avoided, so the length over which the plastic hinges form is different to the span of the portal. The length over which the hinges form will be referred to as the effective length and is defined as follows:

$L_{eff} = L - 2 * h$ [m]

With L [m] : The span of the beam
h [m] : height of the cross-section beam

The assumption will be made that the size of the connection will be equal to the height of the cross-section beam. The assumption is based on the fact that plasticity should be avoided in the connections and the connections should thus be large.

The sacrificial height can be related to the angle of the plastic hinges in the following way, using the effective length:

$s = \frac{1}{2} L_{eff} * \theta$ [m]

To check whether the steel of the DOPS will only deform and not fracture, the strain the steel will experience needs to be calculated. The strain in the beam can be calculated using the following expression:

$\epsilon = \frac{\Delta L}{L}$ [-]

With L [m] : The span of the beam
ΔL [m] : The length of the beam expansion

The problem with this formula for calculating the strain is that it gives the average strain throughout the entire beam, which is substantially lower than the local strain that will occur in the beam. In the beam, plastic hinges will form, and at these places the most strain will occur. To ensure that the DOPS will not fracture, the local strain at these points will need to be within reason.

The solution to obtaining the local strain comes from the curvature. The curvature of the beam can relate to the strain in the following way (Bucciarelli, 2004):

$\epsilon = \kappa * y$ [-]

With κ [m^{-1}] : curvature of the beam

y [m] : distance from the neutral axis of the beam

and the curvature can be defined and related to the angle of bending in the following way:

$\kappa = \frac{d\phi}{dx} = \frac{\theta}{h}$ [m^{-1}]

With θ [-] : angle of bending hinge

h [m] : height of cross-section

dx in this case is the length over which the beam will plastically deform, also known as the plastic hinge length. It is assumed that the length of the plastic hinge is equal to the height of the beam.

According to the NEN-EN-1993-1-1, steel cross-sections are required to have a ductility of at least 15% (European Committee for Standardization, 2022, p. 29), so the maximum theoretical strain ε would be 15%. This strain is only due to tension, while the DOPS will plastically deformation occur due to a moment. The context of this requirement is thus different to the mechanism that will occur at the DOPS. This maximum still gives insight into the maximum strain before failure due to bending before absolute failure. To stay conservative, a factor of safety will be included, so a maximum strain due to bending of 10% will be considered.

The final thing that needs to be added to this model is a factor that accounts for the part of the DOPS that gets hit. The impact load the DOPS will absorb won't be carried by just one portal of the DOPS, but multiple parts of the structure. Because of this, the maximum impact energy one portal of the DOPS will absorb won't be equal to the impact energy of the dropped object. How much energy one portal of the DOPS needs to absorb is dependent on the following aspects:

- The size of the dropped object
- The part of the DOPS that gets hit by the dropped object.
- The centre-to-centre distance of the beams of the DOPS

To account for the uncertainty of how the energy will be distributed throughout the DOPS, the following factor will be used.

$$\beta = \frac{1}{n} * \gamma$$

With n [-] : the number of beams hit by the dropped object
γ [-] : safety factor to account for the uncertainty, value of 1.4

The safety factor has been added to account for the uncertainty of the drop location and the possibility of uneven weight distribution throughout the dropped object. This value has been set at 1.4. This value is based on the assumption that if an object hits two beams, the maximum impact energy in one beam will be 70% of the total impact energy.

5.3 Failure mechanics of DOPS

When it comes to the structural failure of the DOPS, different failure mechanisms are possible. The following failure mechanisms will be accounted for:

- Fracture due to bending in the beam
- Buckling of the columns
- Plate buckling of the beam
- Lateral torsion buckling of the beam

Bending in the beam

Bending in the beam will be the primary way the DOPS will absorb the impact energy. However, when the bending becomes excessive, the maximum strain the beam can handle will be surpassed, and fracture will occur. The maximum strain that will occur in the beams thus needs to stay within the boundaries mentioned in the previous Paragraph 5.2. The strain is linked to the plastic moment capacity of the beam, so the cross-sections with the smallest plastic moment capacity are most vulnerable for this failure mechanism.

Buckling of the columns

Buckling of the columns that support the main beam will cause the DOPS to lose its stability. The buckling capacity of the columns will be calculated using the Euler buckling capacity formula (TU Delft, z.d.):

$$N_{buc,Euler} = \frac{\pi^2 EI}{l_{buc}^2} \quad [N]$$

With EI [Nm²] : Young's modulus * moment of inertia of beam
l_{buc} [m] : buckling length, 2 * the height of the column

The weaker side of the cross-section is more susceptible to buckling, so during the design it is of importance that only the stronger side of the cross-section gets loaded by buckling.

Plate buckling of the beam

Plate buckling is a failure mechanism that can occur locally in either the flanges or the body of a cross-section. The capacity can be calculated with the following formula (INSDAG, n.d.):

$$\sigma_{cr} = \frac{k\pi^2 E}{12(1-\nu^2)\left(\frac{b}{t}\right)^2} \quad [N/m^2]$$

With
- k [-] : Local buckling coefficient
- E [N/m^2] : Young's modulus
- v [-] : Poisson's ratio
- b [m] : width of plate
- t [m] : thickness of plate

The capacity to resist plate buckling is dependent on the ratio between the width and thickness, and the coefficient k. The flanges of beams are primarily susceptible to plate buckling because of their poor width-to-thickness ratio. The HE or IPE cross-sections are most vulnerable to this failure mechanism, but RHS and other profiles can still be susceptible to this failure mechanism, so it also needs to be checked.

For the local buckling coefficient k, the following values will be used for the flanges (Reis & Oliveira Pedro, 2019):

- For HE and IPE cross-sections: 0.43
- For RHS and other types of cross-sections: 4.

Lateral torsion buckling of the beam

The failure mechanism lateral torsion buckling (LTB) will cause the beam to start to rotate and thus lose its stability. This failure mechanism is especially prevalent for slender cross-sections, so both HE and IPE profiles will be vulnerable to this failure mechanism. The moment capacity will be calculated with the following formula (Abspoel et al., 2013, p. 76):

$$M_{cr} = \frac{\pi}{L_g}\sqrt{EI_Z GI_t + \left(\frac{\pi}{L_g}\right)^2 EI_z EI_w}$$

With
- L_g [m] : distance between lateral supports
- E [N/m^2] : Young's modulus
- G [N/m^2] : Shear modulus
- I_z [m^4] : Moment of inertia in relevant direction.
- I_t [m^3] : Torsion resistance
- I_w [m^6] : Warping resistance

This formula only gives the theoretical value of the lateral torsion capacity, so in reality the capacity will be different. This formula, however, can still give an indication of the

critical value (Abspoel et al., 2013, p. 77). The value gained from this formula will be used to see if lateral torsion buckling will be a problem, which it won't be if the value from this formula is far above the plastic moment capacity.

The lateral torsion capacity needs to be bigger than the plastic moment capacity to avoid lateral torsion buckling. Deformation due to hitting the plastic moment capacity is preferred because the effects are more predictable and thus easier to design around. The lateral torsion capacity is best increased by reducing the distance between lateral supports.

The Lateral Torsion Moment capacity will only be calculated for IPE and HE cross-sections because this failure mechanism is mostly a threat to slender cross-sections.

Considering all these failure mechanisms, they should preferably be avoided. The main way the structure should deform is through controlled plastic deformation due to bending because it is the most predictable. The other failure mechanisms all show much more unpredictable plastic deformation and should preferably be avoided.

6 DOPS design concepts

In this chapter, different design concepts for the dropped objects will be discussed. The different design concepts will be explained and tested on their capacity to absorb the impact energy of dropped objects. The different variants will all consist of different cross-sections and configurations to see how they perform at absorbing the impact load.

For the DOPS, the goal is to design a modular system consisting of a portal frame which can be expanded based on what needs to be protected. For the different variants, the idea is to explore how the system handles the impact load, so the structural system of each variant will stay the same, but the sizes of the profiles or the thickness of certain elements can be adapted based on what needs to be protected.

The following variants will be discussed and tested:

- Variant 1: HE cross-section beams welded to a HE cross-section beam connected to HE columns.
- Variant 2: IPE cross-section beams welded to an IPE cross-section connected to RHS columns.
- Variant 3: A steel plate welded to the top of an RHS cross-section beam connected to HEA columns.

To test the effectiveness of the structures, they will be tested on an impact load of 300 kJ, which corresponds to the falling of a sludge disposal tank in the Auxiliary Laydown TS003 mentioned in Chapter 4. This dropped object generated an impact energy of 294.3 kJ, which will be rounded to 300 kJ. The own weight of the structure will be ignored for the calculations because they are insignificant compared to the force generated by impact.

In the paragraphs to follow, the different variants will all be further worked out in more detail. For each variant, the structural integrity will be checked using the model set up in the previous chapter. All the calculations will be made with Microsoft Excel.

6.1 Variant 1: HE beams and columns

The first variant will test how HE cross-sections perform at absorbing the dropped object impact. Different HEA, HEB and HEM cross-sections will be compared to each other to see which failure mechanisms are most at risk, and which type of HE thus performs best. Then different iterations will be used to see what height of cross-section is at least needed to absorb the energy without structural failure.

The first variant will have the following design features:

- HE beams with a c.t.c distance of 1 metre, covering a 5.8 metre span.
- HE columns with a height of 4 metres plus the crumple zone.
- A moment-fixed connection between beam and column.
- A moment-fixed support between the vessel and column.
- Secondary beams and wind bracing for added structural stability.
- Steel grading on top of the beams so smart objects don't slip through.

An example of what this variant looks like can be seen down below in Figure 6-1e. This example consists of HEA 400 beams and columns, and features multiple portals connected to each other to a length of 6 metres.

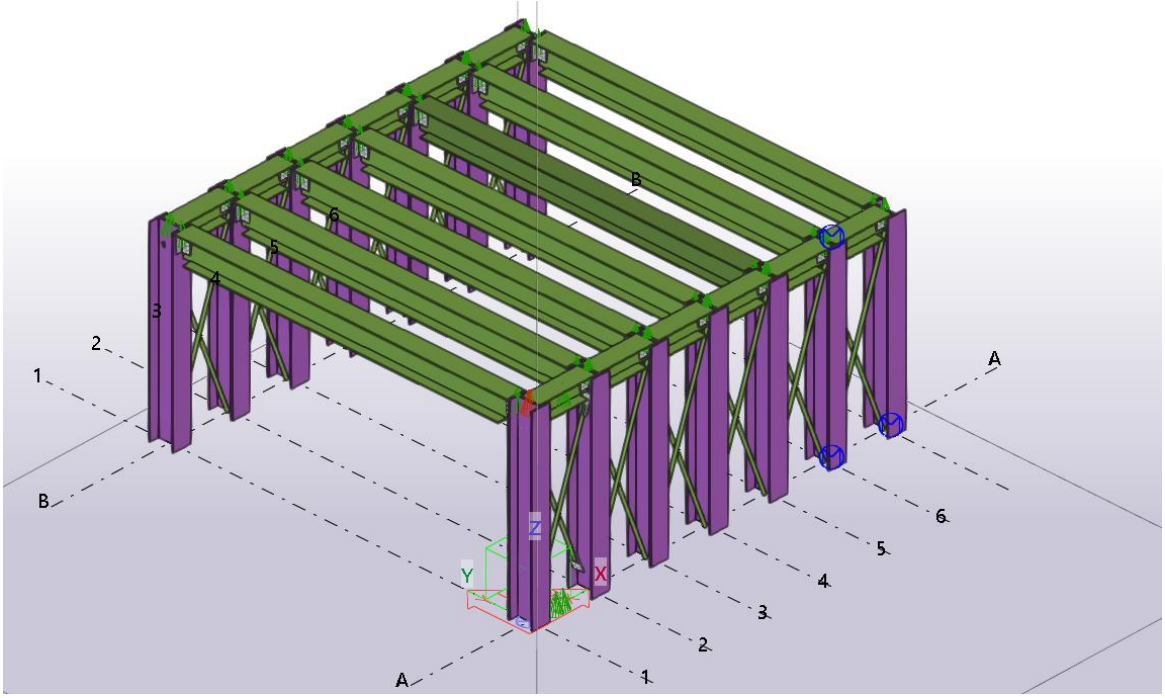

Figure 6-1: Tekla model of first variant

To test the structural performance of this variant, the model built in Paragraph 5.2 will be used. The results of calculations for the different cross-sections can be seen in Table 6-1 below. The full calculations were done in Microsoft Excel and can be found in Appendix E. The sludge disposal tank has a width of 2.4 metres, so at least 2 different beams will be hit, this gives n = 2.

Table 6-1: Results of calculations variant 1

Type of Beam	Type of Column	M_pl: Plastic Moment Capacity (kNm)	s: Sag of Middle (m)	ε: Strain (%)	F: Generated Force (kN)	F_buck: Buckling Column (kN)	F_plate: Plate Buckling of beam (kN)	M_cr: Lateral Torsion Buckling of beam (kNm)	Weight of 1 m DOPS (kg)
HEA 400	HEA 400	943.06	0.14	2.78	2254.32	2356.19	1865.97	1327.43	2056.88
HEB 400	HEB 400	1175.76	0.11	2.23	2821.82	3015.53	3760.77	1866.27	2550.09
HEM 400	HEM 400	1967.77	0.07	1.33	4783.87	5505.45	17014.00	4473.46	4176.88
HEA 300	HEA 300	514.40	0.27	5.10	1182.52	1638.99	746.50	744.87	1477.71
HEB 300	HEB 300	685.86	0.20	3.83	1582.75	2292.84	1865.97	1156.35	1942.69
HEM 300	HEM 300	1420.71	0.09	1.85	3329.79	5451.08	15616.98	4101.40	3899.54

With these results, safety checks can be performed to see whether any of the failure mechanisms will occur. The results of these safety tests can be seen below in Table 6-2.

Table 6-2: Safety checks variant 1

	Unity Check	ε / 10%	F / F_buck	F / F_plate	M_pl / M_cr
Type of Beam	**Type of Column**	**Strain**	**Buckling Column**	**Plate Buckling**	**LTB**
HEA 400	HEA 400	0.28	0.96	1.21	0.71
HEB 400	HEB 400	0.22	0.94	0.75	0.63
HEM 400	HEM 400	0.13	0.87	0.28	0.44
HEA 300	HEA 300	0.51	0.72	1.58	0.69
HEB 300	HEB 300	0.38	0.69	0.85	0.59
HEM 300	HEM 300	0.18	0.61	0.21	0.35

The result of the Unity Checks is mostly good, the only failure mechanism that poses a threat to the structural integrity of the system is plate buckling. This failure mechanism only occurs at HEA type cross-sections and poses less risk to the HEB and HEM types. The Unity Checks also highlight that the HEB 300 cross-section performs the most efficiently, because it is the smallest cross-section where no failure mechanisms occur.

6.2 Variant 2: IPE Beams with RHS columns

The second variant will test how IPE beams respond to the impact load of a critical dropped object. It will also test a different load path compared to the first variant, where the load is first transferred from beam to beam and then to the column. Once again, different iterations will be used to determine the dimensions needed for the cross-sections.

The second variant will have the following design features:

- Secondary IPE beams with a c.t.c distance of 0.8 metres, covering a 5.8 metre span
- Primary IPE beams located between the columns with a span of 2.4 metres.
- Square RHS columns, with a height of 4 metres plus a crumble zone.
- Moment-fixed connection between primary and secondary beams
- Moment-fixed connection between columns and beams
- Find bracing for added stability.
- Steel grading on top of the beams so smart objects don't slip through.

An example of what a configuration of this model could look like can be found in Figure 6-2 down below. This features 3 units next to each other for a total length of 7.2 metres.

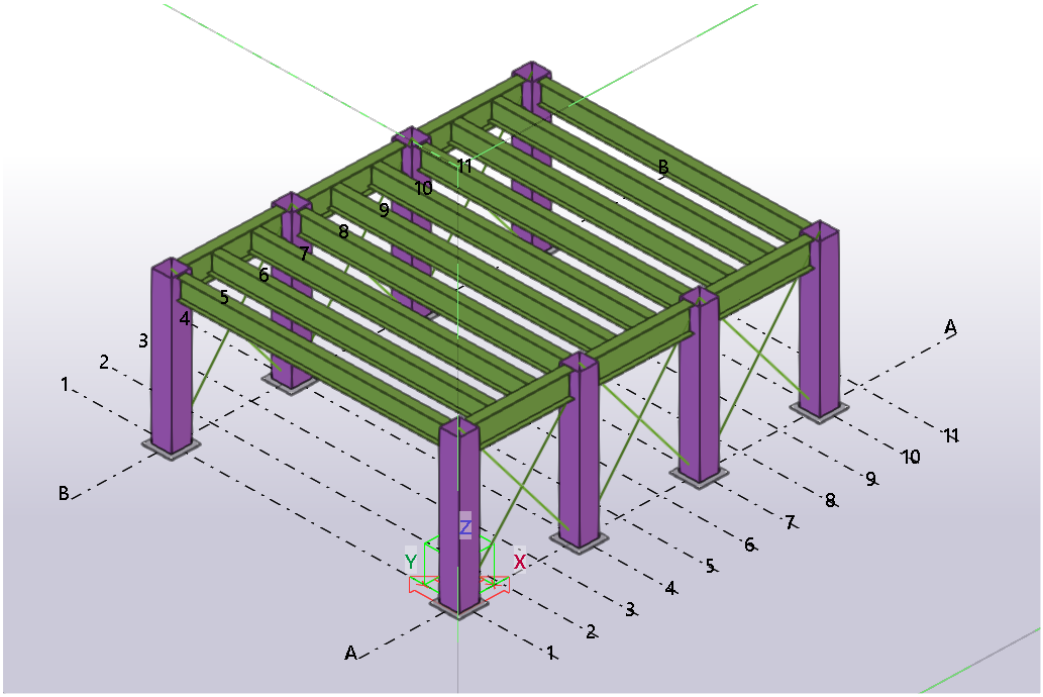

Figure 6-2: Tekla model variant 2

To calculate the structural integrity of this variant, the model built in Paragraph 5.2 will be used again. The model needs to be slightly changed to incorporate the different loading path compared to variant 1. Variant 2 has a load path where the secondary beams first transfer their load to the primary beams and then the columns. This means that the force in a single column will be higher than the generated force in one of the secondary beams. Each column will have to absorb the impact force of 2 beams, so this will have to be accounted for when checking the buckling strength of the columns. This variant has a centre-to-centre distance of 0.8 metres, and the sludge disposal tank has a width of 2.6 metres, so at least three beams will be hit. This gives n = 3.

The primary beams of this variant have been deemed non-critical because of their shorter span compared to the secondary beams and the fact that they are bigger than the secondary beams, because they otherwise can't be connected.

The results of applying the model can be seen below in Table 6-3. Here all the different forces and failure capacities can be found. The full calculations were done in Excel and can be found in Appendix F.

Table 6-3: Results of calculations variant 2

Type of Beam	Type of Column	M_pl: Plastic Moment Capacity (kNm)	s: Sag of Middle (m)	ε: Strain (%)	F: Generated Force (kN)	F_buck: Buckling Column (kN)	F_plate: Plate Buckling of beam (kN)	M_cr: Lateral Torsion Buckling of beam (kNm)	Weight of 1 m DOPS (kg/m)
IPE 500	RHS 300x300x10	787.92	0.11	2.22	1969.81	4470.01	1671.46	443.58	1735.43
IPE 400	RHS 300x300x8	473.57	0.18	3.70	1136.57	3530.51	1115.56	240.87	1328.43
IPE 360	RHS 250x250x8	369.06	0.24	4.74	871.79	1960.01	983.39	178.29	1130.72
IPE 300	RHS 200x200x8	227.40	0.40	7.70	524.76	908.41	666.54	94.51	888.44

Safety checks have been performed with the results from Table 6-3. The results of these safety checks can be found in Table 6-4. Based on these safety checks, the critical failure mechanisms can be found.

Table 6-4: Safety checks variant 2

	Unity Check	ε / 10%	2*F / F_buck	F / F_plate	M_pl / M_cr
Type of Beam	**Type of Column**	**Strain**	**Buckling Column**	**Plate Buckling**	**LTB**
IPE 500	RHS 300x300x10	0.22	0.88	1.18	1.78
IPE 400	RHS 300x300x8	0.37	0.64	1.02	1.97
IPE 360	RHS 250x250x8	0.47	0.89	0.89	2.07
IPE 300	RHS 200x200x8	0.77	1.16	0.79	2.41

The safety checks highlight that this variant is highly vulnerable to loss of local stability, with both Plate Buckling and Lateral Torsion Buckling failing the safety checks. Plate Buckling can be avoided by using smaller profiles that thus lower the maximum force but could still pose a risk.

Lateral Torsion Buckling is unavoidable in the current setup, so a structural design change would be needed to solve this issue. LTB supports halfway across the span could be a solution. $M_{cr} \propto \frac{1}{L_g^2}$ so halving the L_g would increase the M_{cr} by four and thus solve this problem. This would require more material and increase the complexity of the system. IPE profiles are, because of their risk to local stability, not the best for DOPS.

The square RHS profiles perform well at the unity checks and are suitable for use in DOPS. For square RHS profiles, the $I_y = I_z$, which means that it has no weak side when it comes to buckling or bending. This is a valuable aspect for DOPS because it means that the stronger side of the cross-section will always be loaded. A RHS 250x250x8 will at least be needed for buckling of the column to not become a risk.

6.3 Variant 3: Steel plate with RHS beams and HEA columns

The third variant will test how RHS profiles in combination with steel plates perform at absorbing the impact load of dropped objects. At first, the use of only RHS beams will be tested to see their potential as beams. Then steel plates will be added to see how their addition changes the way the impact load is absorbed and if this can lead to a more economic design.

The first variant will have the following design features:

- RHS beams with a c.t.c distance of 1 metre, covering a 5.8 metre span.
- HE columns with a height of 4 metres plus the crumple zone.
- A moment-fixed connection between beam and column.
- A moment-fixed support between the vessel and column.
- Secondary beams and wind bracing for added structural stability.
- Steel grading on top of the beams so smart objects don't slip through.

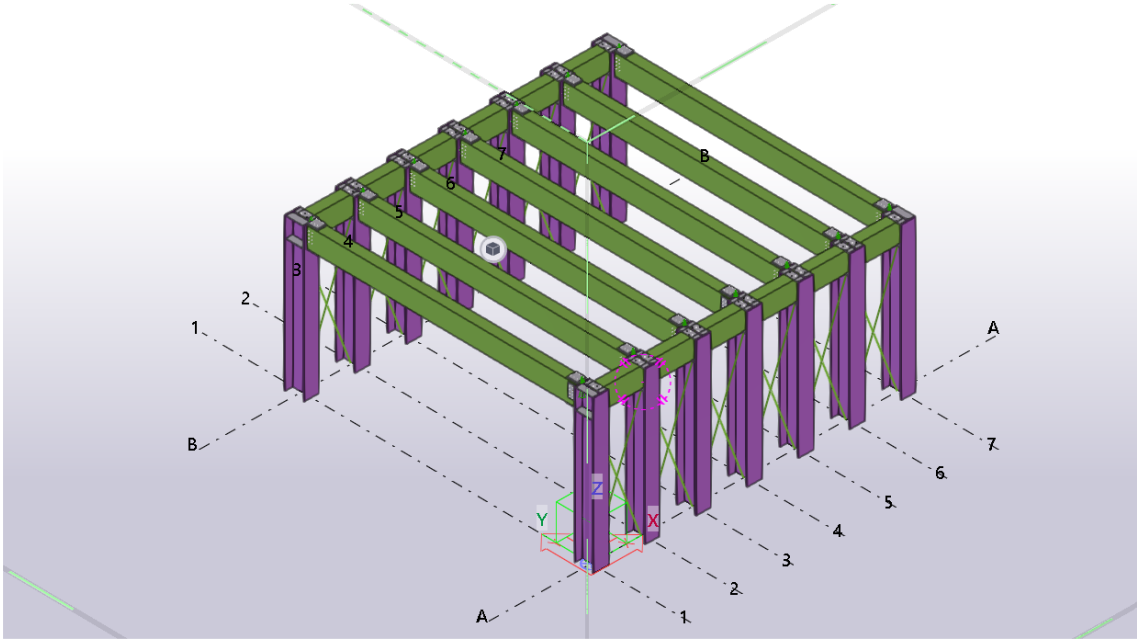

Figure 6-3: Tekla model of variant 3 without steel plate

Using the model from Chapter 5 gives the results that can be seen in Table 6-5 below. Lateral Torsion Buckling has not been calculated because it was deemed to only be a threat to IPE and HE profiles in Paragraph 5.3. The full calculations can be found in Appendix G.

Table 6-5: Results of calculations variant 3 without steel plate

Type of Beam	Type of Column	M_pl: Plastic Moment Capacity (kNm)	s: Sag of Middle (m)	ε: Strain (%)	F: Generated Force (kN)	F_buck: Buckling Column (kN)	F_plate: Plate Buckling of beam (kN)	Weight of 1 m DOPS (kg/m)
RHS 400x200x10	HEA 400	511.20	0.26	5.13	1226.88	2234.08	3796.00	1816.68
RHS 300x200x10	HEB 400	335.69	0.41	7.82	774.66	2641.68	3796.00	2011.64
RHS 300x200x8	HEB 300	276.05	0.49	9.51	637.03	2013.31	1943.55	1569.16
RHS 250x150x10	HEA 300	210.44	0.66	12.47	476.48	1383.63	5061.34	1317.20

Safety checks have been performed with the results from Table 6-5, the results of these safety checks are presented in Table 6-6.

Table 6-6: Safety checks variant 3

	Unity Check	ε / 10%	F / F_buck	F / F_plate
Type of Beam	**Type of Column**	**Strain**	**Buckling Column**	**Plate Buckling**
RHS 400x200x10	HEA 400	0.51	0.55	0.32
RHS 300x200x10	HEB 400	0.78	0.29	0.20
RHS 300x200x8	HEB 300	0.95	0.32	0.33
RHS 250x150x10	HEA 300	1.25	0.34	0.09

The RHS beams perform well when it comes to absorbing the impact load. The use of RHS beams removes the local stability issues that both the HEA and the IPE profiles faced. The RHS deform more when compared to the I-shaped cross-sections. This can be seen as a good thing because it lowers the force generated by the impact load, but it also has downsides. This is because of two things. First, critical shear rates are reached faster and thus lead to structural failure. Second, plastic deformation occurs faster, so lower impact drops might plastically deform the RHS profile and, with that, make repairs necessary.

Now steel plates are added to the structure to see how that changes the way the impact load is absorbed. The structure remains the same, the only thing that changes is the addition of the steel plates. The steel plates will be welded to the RHS beams, and with that, the assumption will be made that they bend as one body.

The plastic deformation of steel plates is a complex process because of the 2D bending behaviour of plates. This makes modelling them difficult, and fully capturing the plastic deformation of plates is outside the scope of this research. To get an idea of the effect of steel plates, the moment of inertia of the plate and the RHS profile will be combined.

The new shape of the cross-section makes it so that the shape factor cannot be used for calculating the plastic moment capacity. So now the plastic moment capacity must be calculated using the plastic neutral axis and the following formula (TU Delft, 2024):

$$M_{pl} = \sum F_i \, r_i \quad \text{[kNm]}$$

With F [kN] : the force, equal to area x yield strength

r [m] : distance from plastic neutral axis

To find the plastic neutral axis, the assumption will be made that the area under tension and the area under compression are the same. The line that separates these areas is the neutral axis (Engineer, n.d.).

The results of calculating the plastic moment capacity and the resulting force can be seen in Table 6-7 down below. The full calculation can be found in Appendix G.

Table 6-7: Results of calculations variant 3 with steel plate

Type of Beam	Type of Column	Thickness plate (m)	M_pl: Plastic Moment Capacity (kNm)	s: Sag of Middle (m)	ε: Strain (%)	F: Generated Force (kN)	Weight per meter (kg/m)
RHS 400x200x10	HEA 400	0.1	1905.06	0.07	1.38	4762.64	6075.12
RHS 300x200x10	HEA 400	0.1	1560.92	0.08	1.68	3746.21	5983.60
RHS 300x200x8	HEA 400	0.05	697.65	0.19	3.76	1641.53	3624.69
RHS 300x100x10	HEA 400	0.05	688.90	0.19	3.81	1620.94	3616.04
RHS 250x150x10	HEA 400	0.025	421.32	0.33	6.23	963.01	2477.79

The use of thick steel plates has a big effect on the plastic moment capacity of the cross-section, making the structure a lot stiffer. This can help with the capacity to absorb higher impact loads. A stiffer structure also means that larger columns and connections are needed. Steel plates are also very heavy and would therefore require a lot of material. The use of steel plates would eliminate the need for steel grating and safe materials there.

Based on these results is the use of thick steel plates is not the most effective due to their large weight. However, the current model used for simulating steel plates is very simplistic and a more detailed model would be needed to gain a better understanding of the effectiveness of thick steel plates.

7 Optimisation of design and FEM analysis

In this chapter, a final design will be tested. This variant will consist of the best elements of the previous variants. This will then be tested in Siemens FEMAP to see if the plastic model from Chapter 5 is accurate.

Load path

The most effective load path is the one from variant 1. This load path absorbs the impact energy by the deformation of the beams, which then redirects the impact energy towards the columns and supports. This load path is very simple, and that is where its effectiveness comes from. A case can be made for the load path of variant 2, with its use of primary and secondary beams, but this adds more components to the system that can be damaged and would have to be replaced. The use of plates has, for now, been deemed ineffective because it makes the structure a lot heavier and stiffer.

Beams

The best choice for the beam is the HEB cross-section. This cross-section is the best for dropped object protection structures, because of its moderately high plastic moment capacity and its good resistance to local instability failure mechanisms. Both the HEA and HEM cross-sections are inferior. The HEA cross-section is too susceptible to plate buckling, and the HEM is too stiff and heavy.

The RHS profiles are also suitable for use in DOPS because local loss of stability is not a big issue, and they are decent at absorbing the impact load via strain. The plastic moment capacity of HEB cross-sections is superior, and that is why they were chosen. When it comes to the weight of the structure, the use of smaller cross-sections for the beam makes for a lighter structure even though the height of the columns has to be increased due to a larger crumble zone.

Columns

The best columns to use for DOPS are square RHS columns. This is because the moments of inertia around the y-axis and z-axis are the same, so they have no weak side that is more at risk of buckling. This is an important aspect for protection against dropped objects because there is a lot of uncertainty when it comes to where an object is going to hit the structure. The HE cross-sections could also be an option with side support to avoid buckling around the weaker axis.

Connections

The connections of the DOPS have not been discussed much in this report, but they are still of importance for the design of the DOPS. For the structural integrity of the DOPS, plastic deformation of the connections is unwanted. This makes it important to

over-dimension both the connection between the vessel and column, and the column and beam. A bolted connection is preferred over welding because a bolted connection allows for easier replacement of broken parts. This leads to a more efficient and sustainable design.

Now the individual parts need to be dimensioned. The dimensioning of the parts has been done by applying the model from Chapter 5. The result can be seen in Table 7-1 down below. The full calculations can be found in Appendix H.

Table 7-1: Results of calculations final variant

Type of Beam	Type of Column	M_pl: Plastic Moment Capacity (kNm)	s: Sag of Middle (m)	ε: Strain (%)	F: Generated Force (kN)	F_buck: Buckling Column (kN)	F_plate: Plate Buckling of beam (kN)	M_cr: Lateral Torsion Buckling of beam (kNm)	Weight of 1 m (kg)
HEB 360	RHS 300x300x6.3	979.80	0.14	2.68	2314.49	2893.68	3098.78	1608.03	1606.86
HEB 340	RHS 300x300x6.3	881.82	0.15	2.98	2066.77	2872.03	2703.70	1463.82	1549.35
HEB 320	RHS 300x300x6.3	787.92	0.17	3.33	1832.38	2846.47	2343.72	1326.77	1492.82
HEB 300	RHS 300x300x6.3	685.86	0.20	3.83	1582.75	2811.49	1865.97	1156.35	1421.25
HEB 280	RHS 300x300x6.3	563.39	0.24	4.66	1290.19	2754.68	1699.90	868.67	1318.09
HEB 260	RHS 300x300x6.3	469.49	0.30	5.59	1067.02	2692.45	1682.31	680.59	1244.39

The safety checks can be seen in the Table 7-2 down below.

Table 7-2: Safety checks final variant

	Unity Check	ε / 10%	F / F_buck	F / F_plate	M_pl / M_cr
Type of Beam	**Type of Column**	**Strain**	**Buckling Column**	**Plate Buckling**	**LTB**
HEB 360	RHS 300x300x6.3	0.27	0.80	0.75	0.61
HEB 340	RHS 300x300x6.3	0.30	0.72	0.76	0.60
HEB 320	RHS 300x300x6.3	0.33	0.64	0.78	0.59
HEB 300	RHS 300x300x6.3	0.38	0.56	0.85	0.59
HEB 280	RHS 300x300x6.3	0.47	0.47	0.76	0.65
HEB 260	RHS 300x300x6.3	0.56	0.40	0.63	0.69

For the final design, the HEB 320 will be used as a beam. This cross-section has been chosen because it performs well at all safety checks. It could be said that the HEB 320 is over-dimensioned because in theory the HEB 260 would also suffice. But a smaller cross-section means that it will plastically deform faster even under smaller loads, thus making repairs necessary faster. To combat this, the HEB 320 has been chosen.

For the column, the RHS 300x300x6.3 has been chosen because it is the smallest cross-section that still has a width of 300 mm (the same as the HEB 320) that does not fail due to buckling.

How this final structure will look can be seen in the figures below.

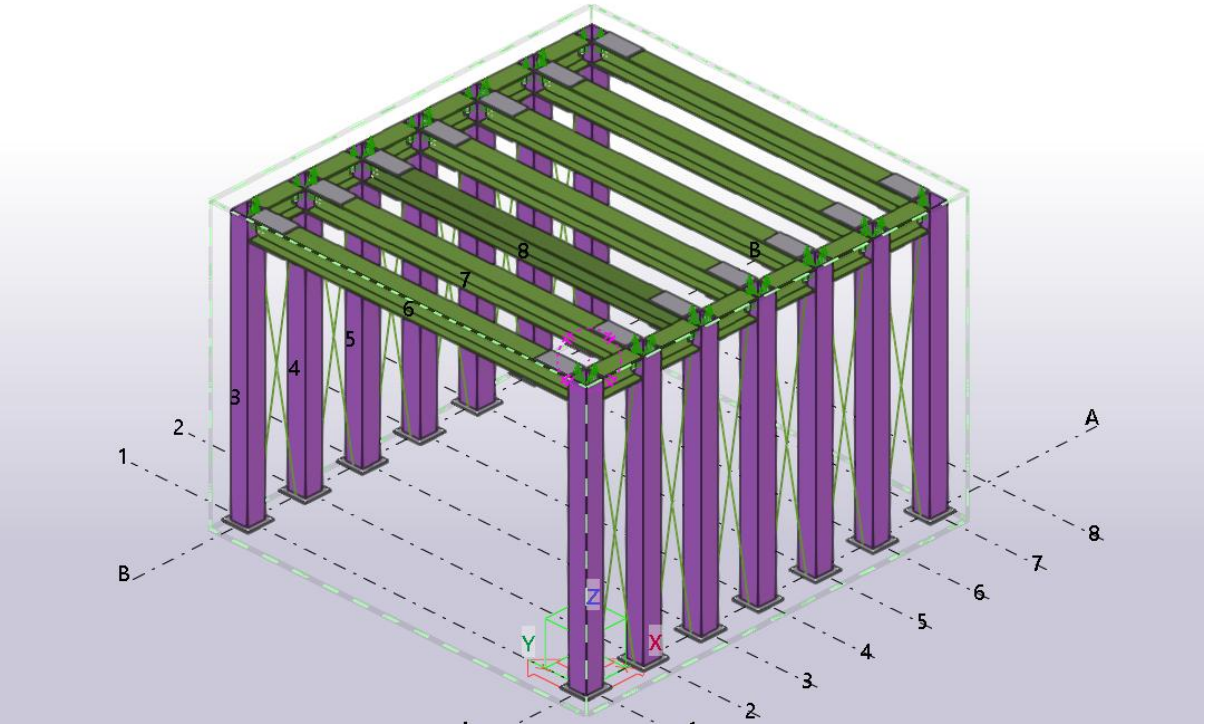

Figure 7-1: Tekla model of final Variant



Figure 7-2: Render of Tekla model final variant

Now will a FEM analysis be performed to see how the results compare to the model, for this analysis, Siemens FEMAP will be used. This model will be performed on the HEB 320 beam to see how the stress distribution, deformations and strains are. As a force, the calculated generated peak force of 1832 kN will be used.

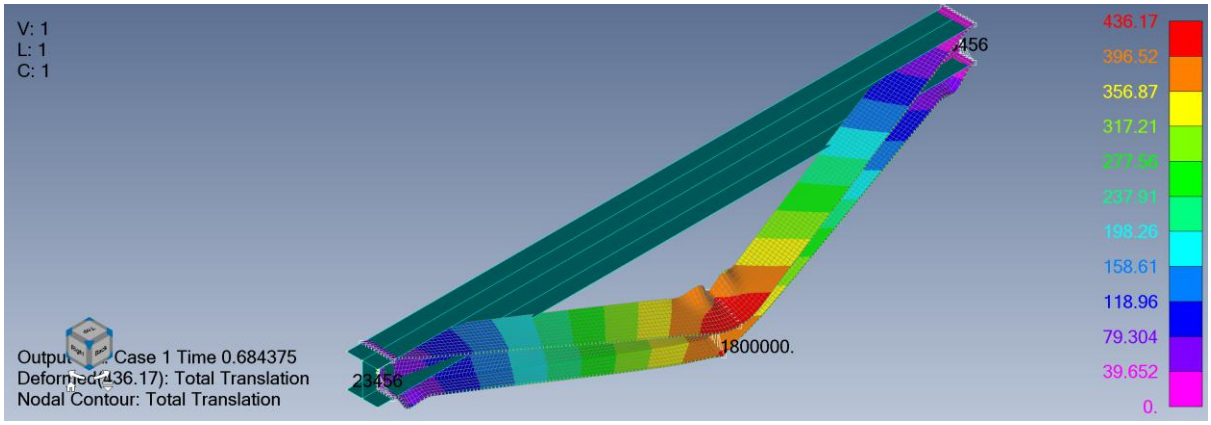

Figure 7-3: FEM analysis total translation, LGDISP on

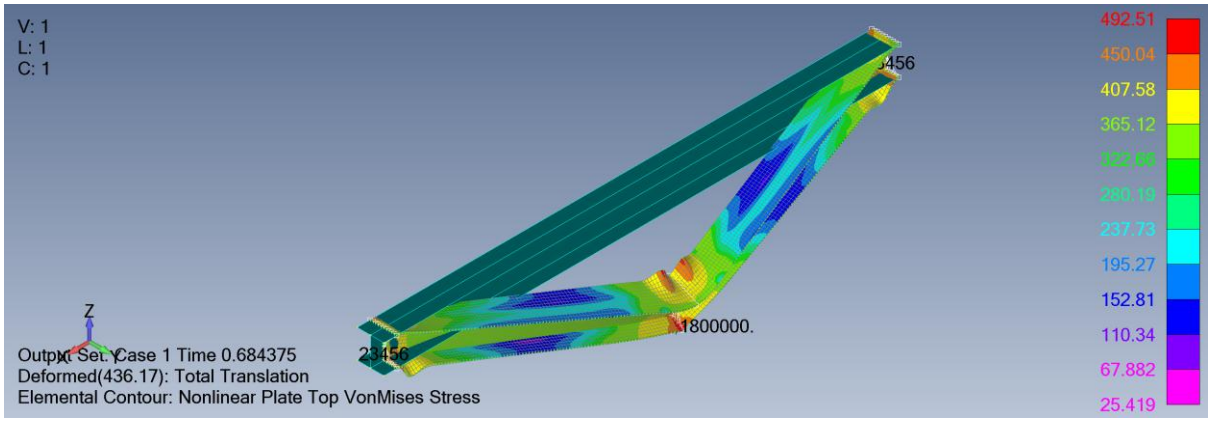

Figure 7-4: FEM analysis VonMises stress, LGDISP on

The FEM analysis gives a different result compared to what the model gives. According to the FEM, plate buckling and lateral torsion buckling will be an issue. The FEM also gives a way larger deformation than was to be expected. These failure mechanisms thus need more attention when designing.

For the FEM analysis, the peak generated force calculated by the model was used. The differences between FEM and model most likely originate from the x1.5 factor used for the peak force. This factor should be lower to better imitate the results gained from the model. Iterating upon this factor gives results that better mirror the ones expected based on the model.

Using a factor of 1.1 gives the results that can be seen in the figures on the next page. With this lower factor, the deformations are closer to the deformations calculated by the model. Comparing the strain of the model and the FEM analysis shows that the strain of the FEM is bigger than the model (~3.33% for the model and ~7.5% for the FEM). The estimation of the length of the plastic hinges is thus off by a bit and also needs some revision. Further research needs to be done to come to more accurate estimates.

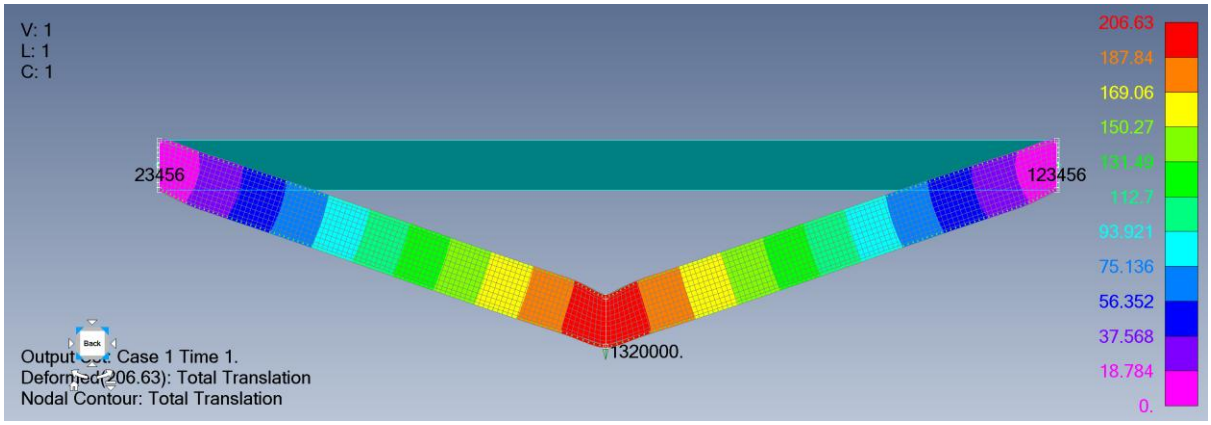

Figure 7-5: Results FEM with factor 1.1 translations, LGDISP off

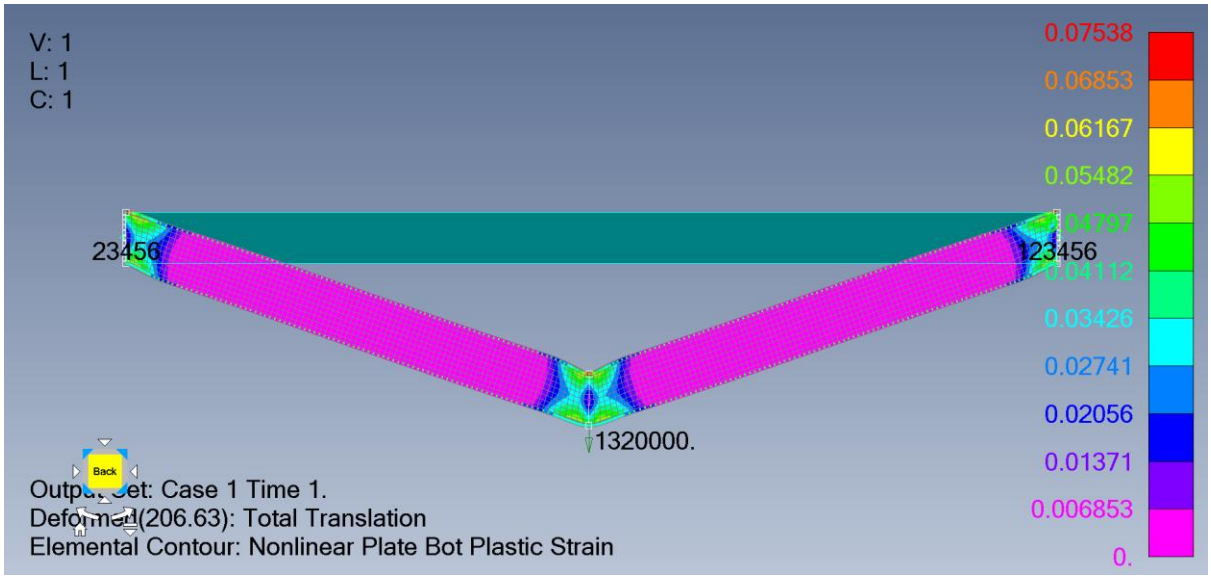

Figure 7-6: Results FEM with factor 1.35 plastic strain, LGDISP off

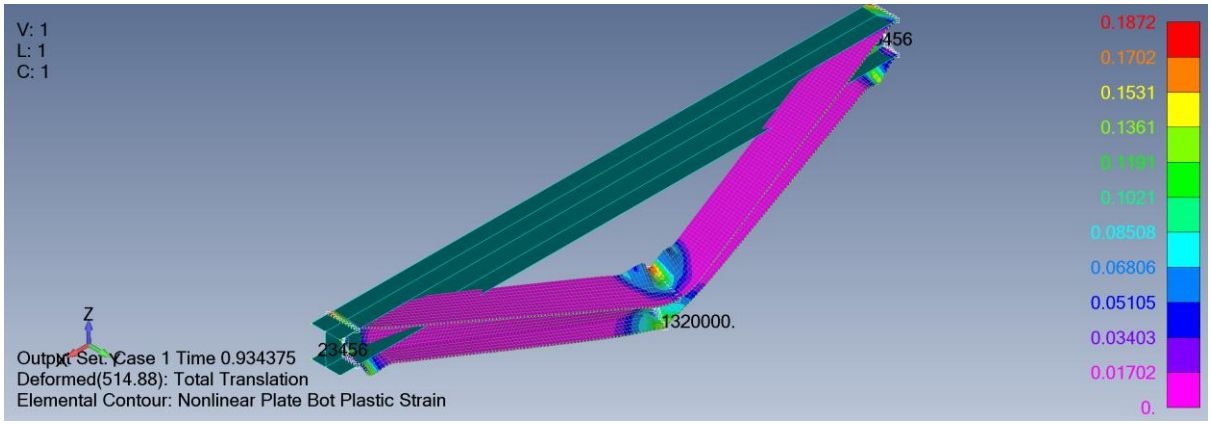

Figure 7-7: Results FEM with factor 1.1, LGDISP on

The beam will still undergo plate buckling and lateral torsion buckling even with the lower peak force factor. This problem still needs to be solved by putting stiffeners in the HEB beam or possibly using a RHS profile. The RHS profile might have the problem that vertical parts will start to buckle, so further research can also focus on this.

8 Discussion

This chapter will discuss some topics that have not been explored (to its fullest extent) in this research. Most of them could be further researched to further optimise and streamline the design of dropped object protection structures.

Effect of stiffer steel

For the design of this DOPS, S355 steel has been used, which means that the material should have a yield strength of 355 N/mm^2. In reality, the material properties are always different to what they should be in theory, so 355 N/mm^2 is a lower boundary of what the real value is. This means that the steel is stiffer in reality, which has consequences for how the structure will respond to the impact load. A stiffer structure means less deformation and thus a higher generated force. This is something that could be researched for a deeper understanding of impact behaviour.

Influence of shear force

In the report, the influence of shear force has not been researched. The reason for this is that bending is prevalent for structural design. With impact loads that are this high, however, failure due to shear could be a possibility; this is something that could be further researched to see the effect of shear force on DOPS.

HEB vs RHS

For the final variant, HEB beams are being used because they were deemed most fit for use in DOPS. However, RHS beams also showed the potential to successfully absorb the impact load. The conclusion stands that HEB beams perform the best, but use of RHS beams could be further explored.

Assumptions and factors in plastic model

The FEM analysis highlighted some flaws in the assumptions made for the plastic deformation model. These assumptions could be further researched for a better model. The assumption made for the peak force and the plastic hinge length need the most attention.

9 Conclusion and recommendations

Based on the research done in the previous chapters, the following conclusions have been made.

The process of designing a dropped object protection structure must start with a risk assessment. With this risk assessment, it is of importance to look thoroughly at the zones and installations that are at risk, and what dropped objects pose the biggest risk. Next to that, it is also important that the chance of occurrence is incorporated into the risk assessment, to come to an economically feasible design. For this FPSO, the critical load that is still within economic feasibility was deemed the dropping of a sludge disposal tank in Auxiliary Laydown TS003 and Main Laydown 1 (TS151) with an impact energy of 294.3 kJ.

For calculating the impact load, the following recommendations are given. First, the resistance can be ignored when calculating the impact load because of its negligible effect. Secondly, the impact energy the DOPS will have to absorb will be lower than the gravitational energy because the dropped object itself also deforms and absorbs a fraction of the impact energy.

For modelling the largest impact loads, a model is needed that accounts for plastic deformation to absorb the impact load. A model that only accounts for elastic deformation will not suffice for these critical loads but could still be used to see what the effect is of dropped objects with smaller loads (loads in the order of ~10 kJ). The model in Paragraph 5.1 can be used for that.

The model made in Paragraph 5.2 models plastic deformation using plastic hinges. This model made some assumptions to get results, but these assumptions were not the most accurate and still need more research to get the most accurate model. The results from the model and FEMAP differ a lot, but some alteration of the factors and assumptions already showed results from the model that come closer to FEMAP. The plastic deformation model can offer some important insights into deformations and give an upper bound of what the expected force is. In its current form, integration with a FEM analysis is recommended to get a better idea of the forces and failure mechanisms.

When it comes to the different failure mechanisms, the design philosophy for DOPS is that deformation due to strain is the most predictable and thus desired. The plastic model is not conservative enough for plate buckling and lateral torsion buckling because these failure mechanisms have been shown to occur in FEMAP. More conservative formulas and predictions are needed and could be further researched.

Based on the different design variants that were tested, the following design recommendations will be made.

Load Path
For the load path of the DOPS, it is recommended to keep it simple. A simple portal structural system in combination with wind bracing will suffice. Trying other configurations did not give a significant decrease in material, and it is thus advised to keep the structure simple.

Beam cross-section
Testing different types of cross-sections showed that the HEB cross-sections perform the best at absorbing the impact load. These HEB cross-sections do need extra countermeasures against local forms of instability, because the FEM analysis revealed that both plate buckling and lateral torsion buckling could be an issue. Countermeasures in the form of lateral support and stiffeners could provide a solution but should be further researched. For now, the HEB has been chosen for the context of this FPSO.

Column cross-section
For the columns, the best cross-sections are square RHS profiles. These are the best because they have no weak side that is susceptible to buckling. This aspect is of value for a DOPS due to the unpredictability of where dropped objects will hit. For the context of this FPSO unit, the RHS 300x300x6.3 has been used for the design.

Detailing
Then finally the detailing. For the connections, it is important that no plastic hinges form here. So, they need to be over-dimensioned to avoid this. The same goes for the connection to the vessel. Preferably, connections that can be taken apart easily should be used, so damaged components can be repaired easily. The last addition to the DOPS should be steel grading to avoid smaller components falling between the structural beams.

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Appendix A: Calculations why drag force can be ignored

The drag force can be calculated with the following formula:

$F_D = \frac{1}{2} * \rho * C_d * A * v^2$ [N]

With: ρ [kg/m^3] : Air density,1.225 kg/m^3

C_d [-] : Drag Coefficient

A [m^2] : Surface of dropped object

v [m/s] : Velocity of dropped object

This example will be about the Sludge Disposal Tanks – full with a mass of 15000 kg dropping. The impact energy without considering the drag force is 294.3 kJ. With the drag force being considered, the impact energy will be as follows.

$$v_{impact} = \sqrt{2 * g * h} = \sqrt{2 * 9.81 * 2} = 6.26\ m/s$$

$$F_D = \frac{1}{2} * 1.025 kg/m^3 * 2 * (3.5m * 2.4m) * (6.26m/s)^2 = 337.86\ N$$

$$E = F * s = 337.86\ N * 2\ m = 675.7\ J = 0.676\ kJ$$

The drag force has a negligible effect on the impact energy and can thus be ignored. In this example, the drag force and energy are also too big because it only calculates with the final velocity and thus in reality the drag force will have even less effect.

Appendix B: Impact loads of all dropped objects

The dropped objects have been sorted by the relevant laydown area and are ordered from least to most impact. The mass comes from information from SBM Offshore.

Dropped Object	Drop Height (m)	Mass of Object (kg)	Laydown area	Shape factor	Energy calculated (kJ)
Liferafts (25 p)	2	180	Auxiliary Laydown TS003	1	3.5316
Liferafts (35 p)	2	280	Auxiliary Laydown TS003	1	5.4936
Cylinders - empty	2	500	Auxiliary Laydown TS003	1	9.81
Cylinders - full	2	1000	Auxiliary Laydown TS003	1	19.62
Provision Containers (food) - empty	2	1500	Auxiliary Laydown TS003	0.75	22.0725
Miscellaneous Consumables Container - Oil greases - empty	2	1500	Auxiliary Laydown TS003	0.75	22.0725
Miscallaneous Consumables Container - Domestic goods - empty	2	1500	Auxiliary Laydown TS003	0.75	22.0725
Machinery/equipment spare parts container - empty	2	2000	Auxiliary Laydown TS003	0.75	29.43
Sand Bagging Tank - empty	2	1500	Auxiliary Laydown TS003	1	29.43
Helifuel Package - Tote Tanks - empty	2	1700	Auxiliary Laydown TS003	1	33.354
Provision Containers (food) - full	2	3500	Auxiliary Laydown TS003	0.75	51.5025
Sludge Disposal Tanks - empty	2	3350	Auxiliary Laydown TS003	1	65.727
Helifuel Package - Tote Tanks - full	2	4500	Auxiliary Laydown TS003	1	88.29
Sand Bagging Tank - full	2	4600	Auxiliary Laydown TS003	1	90.252
Miscallaneous Consumables Container - Domestic goods - full	2	8000	Auxiliary Laydown TS003	0.75	117.72
Miscellaneous Consumables Container - Oil greases - full	2	10000	Auxiliary Laydown TS003	0.75	147.15
Machinery/equipment spare parts container - full	2	10000	Auxiliary Laydown TS003	0.75	147.15
Sludge Disposal Tanks - full	2	15000	Auxiliary Laydown TS003	1	294.3

Waste Skips (garbage) - empty	2	2040	Garbage Platform	0.75	30.0186
Waste Skips (hazardous) - empty	2	2970	Garbage Platform	0.75	43.70355
Waste Skips (garbage) - full	2	7500	Garbage Platform	0.75	110.3625
Waste Skips (hazardous) - full	2	9750	Garbage Platform	0.75	143.47125

Liferafts (25 p)	2	180	Main Laydown 1 TS151	1	3.5316
intelligent pigs from TS043	2	275	Main Laydown 1 TS151	1	5.3955
intelligent pigs from TS042	2	275	Main Laydown 1 TS151	1	5.3955
intelligent pigs from TS041	2	275	Main Laydown 1 TS151	1	5.3955
Cylinders - empty	2	500	Main Laydown 1 TS151	1	9.81
Cylinders - full	2	1000	Main Laydown 1 TS151	1	19.62
Provision Containers (food) - empty	2	1500	Main Laydown 1 TS151	0.75	22.0725
Miscellaneous Consumables Container - Oil greases - empty	2	1500	Main Laydown 1 TS151	0.75	22.0725
Miscallaneous Consumables Container - Domestic goods - empty	2	1500	Main Laydown 1 TS151	0.75	22.0725
Machinery/equipment spare parts container - empty	2	2000	Main Laydown 1 TS151	0.75	29.43
Sand Bagging Tank - empty	2	1500	Main Laydown 1 TS151	1	29.43
Helifuel Package - Tote Tanks - empty	2	1700	Main Laydown 1 TS151	1	33.354
Provision Containers (food) - full	2	3500	Main Laydown 1 TS151	0.75	51.5025
Sludge Disposal Tanks - empty	2	3350	Main Laydown 1 TS151	1	65.727
Tote tanks/ chemicals (20m3) - empty	2	3650	Main Laydown 1 TS151	1	71.613
Helifuel Package - Tote Tanks - full	2	4500	Main Laydown 1 TS151	1	88.29
Sand Bagging Tank - full	2	4600	Main Laydown 1 TS151	1	90.252
Miscallaneous Consumables Container - Domestic goods - full	2	8000	Main Laydown 1 TS151	0.75	117.72

Miscellaneous Consumables Container - Oil greases - full	2	10000	Main Laydown 1 TS151	0.75	147.15
Machinery/equipment spare parts container - full	2	10000	Main Laydown 1 TS151	0.75	147.15
Sludge Disposal Tanks - full	2	15000	Main Laydown 1 TS151	1	294.3
Tote tanks/ chemicals (20m3) - full	2	36000	Main Laydown 1 TS151	1	706.32

Tote Tanks/ Chemicals (1.3m3) - empty	2	121	Tote tank storage area TS101 - level 2	1	2.37402
Tote Tanks/ Chemicals (2m3) - empty	2	186	Tote tank storage area TS101 - level 2	1	3.64932
Tote Tanks/ Chemicals (3m3) - empty	2	400	Tote tank storage area TS101 - level 2	1	7.848
Tote Tanks/ Chemicals (4.5m3) - empty	2	600	Tote tank storage area TS101 - level 2	1	11.772
Tote Tanks/ Chemicals (1.3m3) - full	2	1463	Tote tank storage area TS101 - level 2	1	28.70406
Tote Tanks/ Chemicals (2m3) - full	2	2250	Tote tank storage area TS101 - level 2	1	44.145
Tote Tanks/ Chemicals (3m3) - full	2	3500	Tote tank storage area TS101 - level 2	1	68.67
Tote Tanks/ Chemicals (4.5m3) - full	2	5250	Tote tank storage area TS101 - level 2	1	103.005

Tote Tanks/ chemicals (4.5m3) - empty	2	600	Tote tank storage area TS101 - level 5	1	11.772
Tote tanks/ chemicals (4.5m3) - full	2	5250	Tote tank storage area TS101 - level 5	1	103.005

intelligent pigs from TS043	2	275	Transition laydown (above piperack)	1	5.3955

intelligent pigs from TS042	2	275	Transition laydown (above piperack)	1	5.3955
intelligent pigs from TS041	2	275	Transition laydown (above piperack)	1	5.3955

Appendix C: Derivation of elastic model

Derivation of the first formula:

$E_{spring} = \frac{1}{2} k_{system} * s^2$ gives $s = \sqrt{\frac{2*E_v}{k_{system}}}$

$F = k_{system} * s$ gives $F = \sqrt{2 * E_v * k_{system}} = \sqrt{2 * m * g * h * k_{system}}$

Assuming only deformation due to normal force:

$N = EA * \epsilon$ and $N = \frac{1}{2} F$ gives

$\frac{1}{2} F = EA * \frac{\Delta H}{H}$ gives $F = \frac{2EA}{H} * \Delta H$ so $k = \frac{2EA}{H}$

All this gives the final formula: $F = \sqrt{\frac{4EA}{H} * m * g * h}$

Derivation of the second formula:

For the beam: $s = \frac{1}{48} \frac{F*L^3}{EI}$ gives $F = \frac{48EI}{L^3} * s$ thus $k_{beam} = \frac{48EI}{L^3}$

For the column: $k_{column} = \frac{2EA}{H}$

Assuming the springs are in series $\frac{1}{k_{system}} = \frac{1}{k_{beam}} + \frac{1}{k_{colomn}} = \frac{1}{\frac{48EI}{L^3}} + \frac{1}{\frac{2EA}{H}}$

$$k_{system} = \left(\frac{1}{\frac{48EI}{L^3}} + \frac{1}{\frac{2EA}{H}} \right)^{-1} = \left(\frac{l^3}{48EI} + \frac{H}{2EA} \right)^{-1}$$

Gives: $F = \sqrt{2 * E * k_{system}} = \sqrt{\frac{2*m*g*h}{\frac{L^3}{48EI} + \frac{H}{2EA}}}$

Appendix D: Calculation of elastic model

The following example will be used to demonstrate that an elastic model is not sufficient for DPSO: a portal construction with a HE 300 A profile for both the columns and beam. On the portal, the Sludge Disposal Tanks – full with a mass of 15000 kg will drop from a height of 2 metres.

$$A = 113 * 10^2\ mm^2 = 0.0113\ m^2$$
$$I = 18260 * 10^4 mm^4 = 1.826 * 10^{-4}\ m^4$$
$$E = 210\ GPa = 210 * 10^9\ N/m^2$$
$$l\ =\ 5\ m \qquad H\ =\ 5\ m$$

$$EA = 210 * 10^9\ N/m^2 * 0.0113\ m^2 = 2372 * 10^6\ N$$
$$EI = 210 * 10^9\ N/m^2 * 1.826 * 10^{-4}\ m^4 = 38346 * 10^3\ Nm^2$$

$$F\ =\ \sqrt{\frac{2*m*g*h}{\frac{l^3}{48EI}+\frac{H}{2EA}}} = \sqrt{\frac{2*15000\ kg*9.81\ m/s^2*2\ m}{\frac{(5\ m)^3}{48*38346*10^3 N/m^2}+\frac{5\ m}{2*2372*10^6\ N}}} = 2921404\ N\ \approx\ 3\ \text{MN}$$

A generated force of around 3 Mega Newtons is too high for any normal-sized cross-section to absorb, so an elastic model will generate an unrealistically high force. This is also only the average force, so the peak force will be even higher.

Appendix E: Calculations variant 1

Source: Quick reference

	Type of Steel		Original Unit		Converted Unit				Formula		Unit
	S355									Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))	80769230769	N/m^2
E-modulus	E	210000	N/mm^2	2.1E+11	N/m^2					
Poissons ratio	v	0.3	-	0.3	-				Plastic Moment Capacity	
density	ρ	7850	kg/m^3	7850	kg/m^3	Plastic moment capacity	M_pl	f_y*α*W_y	943057.5	Nm
							M_pl		943.0575	kNm
	Type of Beam									
	HEA 400								Impact Energy	
Shape Factor	α	1.15	-	1.15	-	Distribution Factor	β	(1/(n))*γ	0.7	-
Span	L	5.8	m	5.8	m	impact energy	E_impact	E_dropped object*β	210000	j=Nm
Height of beam	h	390	mm	0.39	m					
Width of beam	b	300	mm	0.3	m				Deformations	
thickness of body	t_b	11	mm	0.011	m	Effective length beam	L_eff	L-2*h	5.02	
thickness of flange	t_f	19	mm	0.019	m	angle of bending	θ	(E_impact)/(4*M_pl)	0.055669988	-
Area	A_beam	159	cm^2	0.0159	m^2	Sag middle beam	s	1/2*L_eff*θ	0.139731671	m
Moment of inertia y	I_y	45069	cm^4	0.00045069	m^4	curvature	κ	θ/h	0.14274356	m^-1
Section modulus y	W_y	2310	cm^3	0.00231	m^3	strain	ε	κ*1/2*h*100%	2.783499415	%
Moment of inertia z	I_z	8564	cm^4	0.00008564	m^4					
Section modulus Z	W_z	571	cm^3	0.000571	m^3				Generated force	
Torsion resistance	I_t	1890384.094	mm^3	1.89038E-06	m^3	Impact force	F	E_impact/s*1.5	2254320.717	N
Warping resistance	I_w	2.94208E+12	mm^6	2.94208E-06	m^6		F		2254.320717	kN
k coefficient flange	k_f	0.43	-	0.43	-					
k coefficient body	k_b	4	-	4	-				Buckling of column	
						Total height column	H_tot	H+s+0.2	4.339731671	m
	Type of column					Buckling capacity column	F_buck	(π^2*E*I_z) / (2*H_tot)^2	2356188.068	N
	HEA 400					Buckling capacity column	F_buck		2356.188068	kN
Column height	H	4	m	4	m					
Height of beam	h_column	390	mm	0.39	m				Plate Buckling of beam	
Width of beam	b_column	300	mm	0.3	m	Plate flange stress capacity	σ_cr_plate_f	(k_f*π^2*E) / (12*(1-ν^2)*(b/t_f)^2)	327362968.2	N/m^2
thickness of body	t_b_column	11	mm	0.011	m	Plate flange Force capacity	F_cr_plate_f	(σ_cr_plate_f*b*t_f) / 1000	1865.968919	kN
thickness of flange	t_f_column	19	mm	0.019	m					
Area of column	A_column	159	cm^2	0.0159	m^2				Lateral Torsion Buckling of beam	
Moment of inertia y	I_y_column	45069	cm^4	0.00045069	m^4	Gravel lengte	L_g	L_g=L	5.8	m
Section modulus y	W_y_column	2310	cm^3	0.00231	m^3	LTB moment capacity	M_cr	(π/L_g) * sqrt(E*I_z*G*I_t + ((π/L_g)^2)*E*I_z*E*I_w))	1327429.056	Nm
Moment of inertia z	I_z_column	8564	cm^4	0.00008564	m^4				1327.429056	kNm
Section modulus Z	W_z_column	571	cm^3	0.000571	m^3					
									Material use of DOPS	
	Dropped Object					Material used for one meter DOPS	m_tot	(L*A_beam+2*H_tot*A_column+2*A_beam)*ρ	2056.884217	kg
	Sludge disposal Tank									
Dropped object energy	E_dropped object	300	kJ	300000	J					
Amount of beams hit	n	2	-	2	-					
factor	γ	1.4	-	1.4	-					

	Type of Steel		Original Unit		Converted Unit				Formula		Unit
	S355									Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))	80769230769	N/m^2
E-modulus	E	210000	N/mm^2	2.1E+11	N/m^2					
Poissons ratio	v	0.3	-	0.3	-				Plastic Moment Capacity	
density	ρ	7850	kg/m^3	7850	kg/m^3	Plastic moment capacity	M_pl	f_y*α*W_y	1175760	Nm
							M_pl		1175.76	kNm
	Type of Beam									
	HEB 400								Impact Energy	
Shape Factor	α	1.15	-	1.15	-	Distribution Factor	β	(1/(n))*γ	0.7	-
Span	L	5.8	m	5.8	m	impact energy	E_impact	E_dropped object*β	210000	j=Nm
Height of beam	h	400	mm	0.4	m					
Width of beam	b	300	mm	0.3	m				Deformations	
thickness of body	t_b	13.5	mm	0.0135	m	Effective length beam	L_eff	L-2*h	5	
thickness of flange	t_f	24	mm	0.024	m	angle of bending	θ	(E_impact)/(4*M_pl)	0.04465197	-
Area	A_beam	197.8	cm^2	0.01978	m^2	Sag middle beam	s	1/2*L_eff*θ	0.111629924	m
Moment of inertia y	I_y	57680	cm^4	0.0005768	m^4	curvature	κ	θ/h	0.111629924	m^-1
Section modulus y	W_y	2880	cm^3	0.00288	m^3	strain	ε	κ*1/2*h*100%	2.232598489	%
Moment of inertia z	I_z	10819	cm^4	0.00010819	m^4					
Section modulus Z	W_z	721	cm^3	0.000721	m^3				Generated force	
Torsion resistance	I_t	3557463.076	mm^3	3.55746E-06	m^3	Impact force	F	E_impact/s*1.5	2821824	N
Warping resistance	I_w	3.81715E+12	mm^6	3.81715E-06	m^6		F		2821.824	kN
k coefficient flange	k_f	0.43	-	0.43	-					
k coefficient body	k_b	4	-	4	-				Buckling of column	
						Total height column	H_tot	H+s+0.2	4.311629924	m
	Type of column					Buckling capacity column	F_buck	(π^2*E*I_z) / (2*H_tot)^2	3015526.954	N
	HEB 400					Buckling capacity column	F_buck		3015.526954	kN
Column height	H	4	m	4	m					
Height of beam	h_column	400	mm	0.4	m				Plate Buckling of beam	
Width of beam	b_column	300	mm	0.3	m	Plate flange stress capacity	σ_cr_plate_f	(k_f*π^2*E) / (12*(1-ν^2)*(b/t_f)^2)	522329832.9	N/m^2
thickness of body	t_b_column	13.5	mm	0.0135	m	Plate flange Force capacity	F_cr_plate_f	(σ_cr_plate_f*b*t_f) / 1000	3760.774797	kN
thickness of flange	t_f_column	24	mm	0.024	m					
Area of column	A_column	197.8	cm^2	0.01978	m^2				Lateral Torsion Buckling of beam	
Moment of inertia y	I_y_column	57680	cm^4	0.0005768	m^4	Gravel lengte	L_g	L_g=L	5.8	m
Section modulus y	W_y_column	2880	cm^3	0.00288	m^3	LTB moment capacity	M_cr	(π/L_g) * sqrt(E*I_z*G*I_t + ((π/L_g)^2)*E*I_z*E*I_w))	1866269.443	Nm
Moment of inertia z	I_z_column	10819	cm^4	0.00010819	m^4				1866.269443	kNm
Section modulus Z	W_z_column	721	cm^3	0.000721	m^3					
									Material use of DOPS	
	Dropped Object					Material used for one meter DOPS	m_tot	(L*A_beam+2*H_tot*A_column+2*A_beam)*ρ	2550.088827	kg
	Sludge disposal Tank									
Dropped object energy	E_dropped object	300	kJ	300000	J					
Amount of beams hit	n	2	-	2	-					
factor	γ	1.4	-	1.4	-					

	Type of Steel		Original Unit		Converted Unit				Formula		Unit
	S355									Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))	80769230769	N/m^2
E-modulus	E	210000	N/mm^2	2.1E+11	N/m^2					
Poissons ratio	v	0.3	-	0.3	-				Plastic Moment Capacity	
density	ρ	7850	kg/m^3	7850	kg/m^3	Plastic moment capacity	M_pl	f_y*α*W_y	1967765	Nm
							M_pl		1967.765	kNm
	Type of Beam									
	HEM 400								Impact Energy	
Shape Factor	α	1.15	-	1.15	-	Distribution Factor	β	(1/(n))*γ	0.7	-
Span	L	5.8	m	5.8	m	impact energy	E_impact	E_dropped object*β	210000	j=Nm
Height of beam	h	432	mm	0.432	m					
Width of beam	b	307	mm	0.307	m				Deformations	
thickness of body	t_b	21	mm	0.021	m	Effective length beam	L_eff	L-2*h	4.936	
thickness of flange	t_f	40	mm	0.04	m	angle of bending	θ	(E_impact)/(4*M_pl)	0.026680015	-
Area	A_beam	325.8	cm^2	0.03258	m^2	Sag middle beam	s	1/2*L_eff*θ	0.065846277	m
Moment of inertia y	I_y	104119	cm^4	0.00104119	m^4	curvature	κ	θ/h	0.061759294	m^-1
Section modulus y	W_y	4820	cm^3	0.00482	m^3	strain	ε	κ*1/2*h*100%	1.334000757	%
Moment of inertia z	I_z	19335	cm^4	0.00019335	m^4					
Section modulus Z	W_z	1260	cm^3	0.00126	m^3				Generated force	
Torsion resistance	I_t	15145906.52	mm^3	1.51459E-05	m^3	Impact force	F	E_impact/s*1.5	4783869.53	N
Warping resistance	I_w	7.4103E+12	mm^6	7.4103E-06	m^6		F		4783.86953	kN
k coefficient flange	k_f	0.43	-	0.43	-					
k coefficient body	k_b	4	-	4	-				Buckling of column	
						Total height column	H_tot	H+s+0.2	4.265846277	m
	Type of column					Buckling capacity column	F_buck	(π^2*E*I_z) / (2*H_tot)^2	5505449.998	N
	HEM 400					Buckling capacity column	F_buck		5505.449998	kN
Column height	H	4	m	4	m					
Height of beam	h_column	432	mm	0.432	m				Plate Buckling of beam	
Width of beam	b_column	307	mm	0.307	m	Plate flange stress capacity	σ_cr_plate_f	(k_f*π^2*E) / (12*(1-v^2)*(b/t_f)^2)	1385504973	N/m^2
thickness of body	t_b_column	21	mm	0.021	m	Plate flange Force capacity	F_cr_plate_f	(σ_cr_plate_f*b*t_f) / 1000	17014.00107	kN
thickness of flange	t_f_column	40	mm	0.04	m					
Area of column	A_column	325.8	cm^2	0.03258	m^2				Lateral Torsion Buckling of beam	
Moment of inertia y	I_y_column	104119	cm^4	0.00104119	m^4	Gravel lengte	L_g	L_g=L	5.8	m
Section modulus y	W_y_column	4820	cm^3	0.00482	m^3	LTB moment capacity	M_cr	(π/L_g) * sqrt(E*I_z*G*I_t + ((π/L_g)^2)*E*I_z*E*I_w))	4473457.587	Nm
Moment of inertia z	I_z_column	19335	cm^4	0.00019335	m^4				4473.457587	kNm
Section modulus Z	W_z_column	1260	cm^3	0.00126	m^3					
									Material use of DOPS	
	Dropped Object					Material used for one meter DOPS	m_tot	(L*A_beam+2*H_tot*A_column+2*A_beam)*ρ	4176.879366	kg
	Sludge disposal Tank									
Dropped object energy	E_dropped object	300	kJ	300000	J					
Amount of beams hit	n	2	-	2	-					
factor	γ	1.4	-	1.4	-					

	Type of Steel		Original Unit		Converted Unit				Formula		Unit
	S355									Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))	80769230769	N/m^2
E-modulus	E	210000	N/mm^2	2.1E+11	N/m^2					
Poissons ratio	v	0.3	-	0.3	-				Plastic Moment Capacity	
density	ρ	7850	kg/m^3	7850	kg/m^3	Plastic moment capacity	M_pl	f_y*α*W_y	514395	Nm
							M_pl		514.395	kNm
	Type of Beam									
	HEA 300								Impact Energy	
Shape Factor	α	1.15	-	1.15	-	Distribution Factor	β	(1/(n))*γ	0.7	-
Span	L	5.8	m	5.8	m	impact energy	E_impact	E_dropped object*β	210000	j=Nm
Height of beam	h	290	mm	0.29	m					
Width of beam	b	300	mm	0.3	m				Deformations	
thickness of body	t_b	8.5	mm	0.0085	m	Effective length beam	L_eff	L-2*h	5.22	
thickness of flange	t_f	14	mm	0.014	m	angle of bending	θ	(E_impact)/(4*M_pl)	0.102061645	-
Area	A_beam	112.5	cm^2	0.01125	m^2	Sag middle beam	s	1/2*L_eff*θ	0.266380894	m
Moment of inertia y	I_y	18263	cm^4	0.00018263	m^4	curvature	κ	θ/h	0.351936708	m^-1
Section modulus y	W_y	1260	cm^3	0.00126	m^3	strain	ε	κ*1/2*h*100%	5.103082262	%
Moment of inertia z	I_z	6310	cm^4	0.0000631	m^4					
Section modulus Z	W_z	421	cm^3	0.000421	m^3				Generated force	
Torsion resistance	I_t	851730.8217	mm^3	8.51731E-07	m^3	Impact force	F	E_impact/s*1.5	1182517.241	N
Warping resistance	I_w	1.19977E+12	mm^6	1.19977E-06	m^6		F		1182.517241	kN
k coefficient flange	k_f	0.43	-	0.43	-					
k coefficient body	k_b	4	-	4	-				Buckling of column	
						Total height column	H_tot	H+s+0.2	4.466380894	m
	Type of column					Buckling capacity column	F_buck	(π^2*E*I_z) / (2*H_tot)^2	1638992.227	N
	HEA 300					Buckling capacity column	F_buck		1638.992227	kN
Column height	H	4	m	4	m					
Height of beam	h_column	290	mm	0.29	m				Plate Buckling of beam	
Width of beam	b_column	300	mm	0.3	m	Plate flange stress capacity	σ_cr_plate_f	(k_f*π^2*E) / (12*(1-v^2)*(b/t_f)^2)	177737234.8	N/m^2
thickness of body	t_b_column	8.5	mm	0.0085	m	Plate flange Force capacity	F_cr_plate_f	(σ_cr_plate_f*b*t_f) / 1000	746.4963862	kN
thickness of flange	t_f_column	14	mm	0.014	m					
Area of column	A_column	112.5	cm^2	0.01125	m^2				Lateral Torsion Buckling of beam	
Moment of inertia y	I_y_column	18263	cm^4	0.00018263	m^4	Gravel lengte	L_g	L_g=L	5.8	m
Section modulus y	W_y_column	1260	cm^3	0.00126	m^3	LTB moment capacity	M_cr	(π/L_g) * sqrt(E*I_z*G*I_t + ((π/L_g)^2)*E*I_z*E*I_w))	744867.2938	Nm
Moment of inertia z	I_z_column	6310	cm^4	0.0000631	m^4				744.8672938	kNm
Section modulus Z	W_z_column	421	cm^3	0.000421	m^3					
									Material use of DOPS	
	Dropped Object					Material used for one meter DOPS	m_tot	(L*A_beam+2*H_tot*A_column+2*A_beam)*ρ	1477.712025	kg
	Sludge disposal Tank									
Dropped object energy	E_dropped object	300	kJ	300000	J					
Amount of beams hit	n	2	-	2	-					
factor	γ	1.4	-	1.4	-					

	Type of Steel		Original Unit		Converted Unit				Formula		Unit
	S355									Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))	80769230769	N/m^2	
E-modulus	E	210000	N/mm^2	2.1E+11	N/m^2						
Poissons ratio	v	0.3	-	0.3	-				Plastic Moment Capacity		
density	ρ	7850	kg/m^3	7850	kg/m^3	Plastic moment capacity	M_pl	f_y*α*W_y	685860	Nm	
							M_pl		685.86	kNm	
	Type of Beam										
	HEB 300								Impact Energy		
Shape Factor	α	1.15	-	1.15	-	Distribution Factor	β	(1/(n))*γ	0.7	-	
Span	L	5.8	m	5.8	m	impact energy	E_impact	E_dropped object*β	210000	j=Nm	
Height of beam	h	300	mm	0.3	m						
Width of beam	b	300	mm	0.3	m				Deformations		
thickness of body	t_b	11	mm	0.011	m	Effective length beam	L_eff	L-2*h	5.2		
thickness of flange	t_f	19	mm	0.019	m	angle of bending	θ	(E_impact)/(4*M_pl)	0.076546234	-	
Area	A_beam	149.1	cm^2	0.01491	m^2	Sag middle beam	s	1/2*L_eff*θ	0.199020208	m	
Moment of inertia y	I_y	25166	cm^4	0.00025166	m^4	curvature	κ	θ/h	0.255154113	m^-1	
Section modulus y	W_y	1680	cm^3	0.00168	m^3	strain	ε	κ*1/2*h*100%	3.827311696	%	
Moment of inertia z	I_z	8563	cm^4	0.00008563	m^4						
Section modulus Z	W_z	571	cm^3	0.000571	m^3				Generated force		
Torsion resistance	I_t	1850454.094	mm^3	1.85045E-06	m^3	Impact force	F	E_impact/s*1.5	1582753.846	N	
Warping resistance	I_w	1.68779E+12	mm^6	1.68779E-06	m^6		F		1582.753846	kN	
k coefficient flange	k_f	0.43	-	0.43	-						
k coefficient body	k_b	4	-	4	-				Buckling of column		
						Total height column	H_tot	H+s+0.2	4.399020208	m	
	Type of column					Buckling capacity column	F_buck	(π^2*E*I_z) / (2*H_tot)^2	2292836.458	N	
	HEB 300					Buckling capacity column	F_buck		2292.836458	kN	
Column height	H	4	m	4	m						
Height of beam	h_column	300	mm	0.3	m				Plate Buckling of beam		
Width of beam	b_column	300	mm	0.3	m	Plate flange stress capacity	σ_cr_plate_f	(k_f*π^2*E) / (12*(1-v^2)*(b/t_f)^2)	327362968.2	N/m^2	
thickness of body	t_b_column	11	mm	0.011	m	Plate flange Force capacity	F_cr_plate_f	(σ_cr_plate_f*b*t_f) / 1000	1865.968919	kN	
thickness of flange	t_f_column	19	mm	0.019	m						
Area of column	A_column	149.1	cm^2	0.01491	m^2				Lateral Torsion Buckling of beam		
Moment of inertia y	I_y_column	25166	cm^4	0.00025166	m^4	Gravel lengte	L_g	L_g=L	5.8	m	
Section modulus y	W_y_column	1680	cm^3	0.00168	m^3	LTB moment capacity	M_cr	(π/L_g) * sqrt(E*I_z*G*I_t + ((π/L_g)^2)*E*I_z*E*I_w))	1156347.678	Nm	
Moment of inertia z	I_z_column	8563	cm^4	0.00008563	m^4				1156.347678	kNm	
Section modulus Z	W_z_column	571	cm^3	0.000571	m^3						
									Material use of DOPS		
	Dropped Object					Material used for one meter DOPS	m_tot	(L*A_beam+2*H_tot*A_column+2*A_beam)*ρ	1942.692743	kg	
	Sludge disposal Tank										
Dropped object energy	E_dropped object	300	kJ	300000	J						
Amount of beams hit	n	2	-	2	-						
factor	γ	1.4	-	1.4	-						

	Type of Steel		Original Unit		Converted Unit				Formula		Unit
	S355									Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))	80769230769	N/m^2	
E-modulus	E	210000	N/mm^2	2.1E+11	N/m^2						
Poissons ratio	v	0.3	-	0.3	-				Plastic Moment Capacity		
density	ρ	7850	kg/m^3	7850	kg/m^3	Plastic moment capacity	M_pl	f_y*α*W_y	1420710	Nm	
							M_pl		1420.71	kNm	
	Type of Beam										
	HEM 300								Impact Energy		
Shape Factor	α	1.15	-	1.15	-	Distribution Factor	β	(1/(n))*γ	0.7	-	
Span	L	5.8	m	5.8	m	impact energy	E_impact	E_dropped object*β	210000	j=Nm	
Height of beam	h	340	mm	0.34	m						
Width of beam	b	310	mm	0.31	m				Deformations		
thickness of body	t_b	21	mm	0.021	m	Effective length beam	L_eff	L-2*h	5.12		
thickness of flange	t_f	39	mm	0.039	m	angle of bending	θ	(E_impact)/(4*M_pl)	0.036953354	-	
Area	A_beam	303.1	cm^2	0.03031	m^2	Sag middle beam	s	1/2*L_eff*θ	0.094600587	m	
Moment of inertia y	I_y	59201	cm^4	0.00059201	m^4	curvature	κ	θ/h	0.108686336	m^-1	
Section modulus y	W_y	3480	cm^3	0.00348	m^3	strain	ε	κ*1/2*h*100%	1.847667715	%	
Moment of inertia z	I_z	19403	cm^4	0.00019403	m^4						
Section modulus Z	W_z	1250	cm^3	0.00125	m^3				Generated force		
Torsion resistance	I_t	14075786.81	mm^3	1.40758E-05	m^3	Impact force	F	E_impact/s*1.5	3329789.063	N	
Warping resistance	I_w	4.38603E+12	mm^6	4.38603E-06	m^6		F		3329.789063	kN	
k coefficient flange	k_f	0.43	-	0.43	-						
k coefficient body	k_b	4	-	4	-				Buckling of column		
						Total height column	H_tot	H+s+0.2	4.294600587	m	
	Type of column					Buckling capacity column	F_buck	(π^2*E*I_z) / (2*H_tot)^2	5451077.721	N	
	HEM 300					Buckling capacity column	F_buck		5451.077721	kN	
Column height	H	4	m	4	m						
Height of beam	h_column	340	mm	0.34	m				Plate Buckling of beam		
Width of beam	b_column	310	mm	0.31	m	Plate flange stress capacity	σ_cr_plate_f	(k_f*π^2*E) / (12*(1-v^2)*(b/t_f)^2)	1291726840	N/m^2	
thickness of body	t_b_column	21	mm	0.021	m	Plate flange Force capacity	F_cr_plate_f	(σ_cr_plate_f*b*t_f) / 1000	15616.9775	kN	
thickness of flange	t_f_column	39	mm	0.039	m						
Area of column	A_column	303.1	cm^2	0.03031	m^2				Lateral Torsion Buckling of beam		
Moment of inertia y	I_y_column	59201	cm^4	0.00059201	m^4	Gravel lengte	L_g	L_g=L	5.8	m	
Section modulus y	W_y_column	3480	cm^3	0.00348	m^3	LTB moment capacity	M_cr	(π/L_g) * sqrt(E*I_z*G*I_t + ((π/L_g)^2)*E*I_z*E*I_w))	4101395.953	Nm	
Moment of inertia z	I_z_column	19403	cm^4	0.00019403	m^4				4101.395953	kNm	
Section modulus Z	W_z_column	1250	cm^3	0.00125	m^3						
									Material use of DOPS		
	Dropped Object					Material used for one meter DOPS	m_tot	(L*A_beam+2*H_tot*A_column+2*A_beam)*ρ	3899.539998	kg	
	Sludge disposal Tank										
Dropped object energy	E_dropped object	300	kJ	300000	J						
Amount of beams hit	n	2	-	2	-						
factor	γ	1.4	-	1.4	-						

Appendix F: Calculations variant 2

	Type of Steel		Original Unit		Converted Unit				Formula		Unit
	S355									Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))	80769230769	N/m^2
E-modulus	E	210000	N/mm^2	2.1E+11	N/m^2					
Poissons ratio	v	0.3	-	0.3	-				Plastic Moment Capacity	
density	ρ	7850	kg/m^3	7850	kg/m^3	Plastic moment capacity	M_pl	f_y*α*W_y	787922.5	Nm
							M_pl		787.9225	kNm
	Type of Primary Beam									
	IPE 550								Impact Energy	
length	L_p	2.4	m	2.4	m	Distribution Factor	β	(1/(n))*γ	0.466666667	-
Area	A_p_beam	134.4	cm^2	0.01344	m^2	impact energy	E_impact	E_dropped object*β	140000	j=Nm
	Type of Secondary Beam								Deformations	
	IPE 500					Effective length beam	L_eff	L-2*h	4.8	
Shape Factor	α	1.15	-	1.15	-	angle of bending	θ	(E_impact)/(4*M_pl)	0.044420612	-
Span	L_s	5.8	m	5.8	m	Sag middle beam	s	1/2*L_eff*θ	0.10660947	m
Height of beam	h	500	mm	0.5	m	curvature	κ	θ/h	0.088841225	m^-1
Width of beam	b	200	mm	0.2	m	strain	ε	κ*1/2*h*100%	2.221030622	%
thickness of body	t_b	10.2	mm	0.0102	m					
thickness of flange	t_f	16	mm	0.016	m				Generated force	
Area	A_s_beam	115.5	cm^2	0.01155	m^2	Impact force	F	E_impact/s*1.5	1969806.25	N
Moment of inertia y	I_y	48200	cm^4	0.000482	m^4		F		1969.80625	kN
Section modulus y	W_y	1930	cm^3	0.00193	m^3					
Moment of inertia z	I_z	2142	cm^4	0.00002142	m^4				Buckling of column	
Section modulus Z	W_z	214	cm^3	0.000214	m^3	Total height column	H_tot	H+s+0.2	4.30660947	m
Torsion resistance	I_t	892870.5684	mm^3	8.92871E-07	m^3	Buckling capacity column	F_buck	(π^2*E*I_z) / (2*H_tot)^2	4470005.416	N
Warping resistance	I_w	1.24937E+12	mm^6	1.24937E-06	m^6	Buckling capacity column	F_buck		4470.005416	kN
k coefficient flange	k_f	0.43	-	0.43	-					
k coefficient body	k_b	4	-	4	-				Plate Buckling of beam	
						Plate flange stress capacity	σ_cr_plate_f	(k_f*π^2*E) / (12*(1-v^2)*(b/t_f)^2)	522329832.9	N/m^2
	Type of column					Plate flange Force capacity	F_cr_plate_f	(σ_cr_plate_f*b*t_f) / 1000	1671.455465	kN
	RHS 300x300x10									
Column height	H	4	m	4	m				Lateral Torsion Buckling of beam	
Height of beam	h_column	300	mm	0.3	m	Gravel lengte	L_g	L_g=L	5.8	m
Width of beam	b_column	300	mm	0.3	m	LTB moment capacity	M_cr	(π/L_g) * sqrt(E*I_z*G*I_t + ((π/L_g)^2)*E*I_z*E*I_w))	443576.3482	Nm
thickness of body	t_b_column	10	mm	0.01	m				443.5763482	kNm
thickness of flange	t_f_column	0	mm	0	m					
Area of column	A_column	115	cm^2	0.0115	m^2				Material use of DOPS	
Moment of inertia y	I_y_column	16000	cm^4	0.00016	m^4	Material of 1 unit	m_tot	(2*A_p_beam*L_p+4*A_s_beam*L_s_beam+4*A_column*H_tot)*ρ	4165.02188	kg
Section modulus y	W_y_column	1070	cm^3	0.00107	m^3	material of 1 meter DOPS	m_meter	m_tot/2.4	1735.425783	kg/m
Moment of inertia z	I_z_column	16000	cm^4	0.00016	m^4					
Section modulus Z	W_z_column	1070	cm^3	0.00107	m^3					
	Dropped Object									
	Sludge disposal Tank									
Dropped object energy	E_dropped object	300	kJ	300000	J					
Amount of beams hit	n	3	-	3	-					
factor	γ	1.4	-	1.4	-					

	Type of Steel		Original Unit		Converted Unit				Formula		Unit
	S355									Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))	80769230769	N/m^2
E-modulus	E	210000	N/mm^2	2.1E+11	N/m^2					
Poissons ratio	v	0.3	-	0.3	-				Plastic Moment Capacity	
density	ρ	7850	kg/m^3	7850	kg/m^3	Plastic moment capacity	M_pl	f_y*α*W_y	473570	Nm
							M_pl		473.57	kNm
	Type of Primary Beam									
	IPE 450								Impact Energy	
length	L_p	2.4	m	2.4	m	Distribution Factor	β	(1/(n))*γ	0.466666667	-
Area	A_p_beam	98.82	cm^2	0.009882	m^2	impact energy	E_impact	E_dropped object*β	140000	j=Nm
	Type of Secondary Beam								Deformations	
	IPE 400					Effective length beam	L_eff	L-2*h	5	
Shape Factor	α	1.15	-	1.15	-	angle of bending	θ	(E_impact)/(4*M_pl)	0.073906709	-
Span	L_s	5.8	m	5.8	m	Sag middle beam	s	1/2*L_eff*θ	0.184766772	m
Height of beam	h	400	mm	0.4	m	curvature	κ	θ/h	0.184766772	m^-1
Width of beam	b	180	mm	0.18	m	strain	ε	κ*1/2*h*100%	3.695335431	%
thickness of body	t_b	8.6	mm	0.0086	m					
thickness of flange	t_f	13.5	mm	0.0135	m				Generated force	
Area	A_s_beam	84.46	cm^2	0.008446	m^2	Impact force	F	E_impact/s*1.5	1136568	N
Moment of inertia y	I_y	23130	cm^4	0.0002313	m^4		F		1136.568	kN
Section modulus y	W_y	1160	cm^3	0.00116	m^3					
Moment of inertia z	I_z	1318	cm^4	0.00001318	m^4				Buckling of column	
Section modulus Z	W_z	146	cm^3	0.000146	m^3	Total height column	H_tot	H+s+0.2	4.384766772	m
Torsion resistance	I_t	510754.7221	mm^3	5.10755E-07	m^3	Buckling capacity column	F_buck	(π^2*E*I_z) / (2*H_tot)^2	3530509.209	N
Warping resistance	I_w	4.90048E+11	mm^6	4.90048E-07	m^6	Buckling capacity column	F_buck		3530.509209	kN
k coefficient flange	k_f	0.43	-	0.43	-					
k coefficient body	k_b	4	-	4	-				Plate Buckling of beam	
						Plate flange stress capacity	σ_cr_plate_f	(k_f*π^2*E) / (12*(1-v^2)*(b/t_f)^2)	459078954.7	N/m^2
	Type of column					Plate flange Force capacity	F_cr_plate_f	(σ_cr_plate_f*b*t_f) / 1000	1115.56186	kN
	RHS 300x300x8									
Column height	H	4	m	4	m				Lateral Torsion Buckling of beam	
Height of beam	h_column	300	mm	0.3	m	Gravel lengte	L_g	L_g=L	5.8	m
Width of beam	b_column	300	mm	0.3	m	LTB moment capacity	M_cr	(π/L_g) * sqrt(E*I_z*G*I_t + ((π/L_g)^2)*E*I_z*E*I_w))	240867.4514	Nm
thickness of body	t_b_column	8	mm	0.008	m				240.8674514	kNm
thickness of flange	t_f_column	0	mm	0	m					
Area of column	A_column	92.8	cm^2	0.00928	m^2				Material use of DOPS	
Moment of inertia y	I_y_column	13100	cm^4	0.000131	m^4	Material of 1 unit	m_tot	(2*A_p_beam*L_p+4*A_s_beam*L_s_beam+4*A_column*H_tot)*ρ	3188.225239	kg
Section modulus y	W_y_column	875	cm^3	0.000875	m^3	material of 1 meter DOPS	m_meter	m_tot/2.4	1328.427183	kg/m
Moment of inertia z	I_z_column	13100	cm^4	0.000131	m^4					
Section modulus Z	W_z_column	875	cm^3	0.000875	m^3					
	Dropped Object									
	Sludge disposal Tank									
Dropped object energy	E_dropped object	300	kJ	300000	J					
Amount of beams hit	n	3	-	3	-					
factor	γ	1.4	-	1.4	-					

	Type of Steel		Original Unit		Converted Unit				Formula		Unit
	S355									Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))	80769230769	N/m^2
E-modulus	E	210000	N/mm^2	2.1E+11	N/m^2					
Poissons ratio	v	0.3	-	0.3	-				Plastic Moment Capacity	
density	ρ	7850	kg/m^3	7850	kg/m^3	Plastic moment capacity	M_pl	f_y*α*W_y	369058	Nm
							M_pl		369.058	kNm
	Type of Primary Beam									
	IPE 400								Impact Energy	
length	L_p	2.4	m	2.4	m	Distribution Factor	β	(1/(n))*γ	0.466666667	-
Area	A_p_beam	84.46	cm^2	0.008446	m^2	impact energy	E_impact	E_dropped object*β	140000	j=Nm
	Type of Secondary Beam								Deformations	
	IPE 360					Effective length beam	L_eff	L-2*h	5.08	
Shape Factor	α	1.15	-	1.15	-	angle of bending	θ	(E_impact)/(4*M_pl)	0.094836042	-
Span	L_s	5.8	m	5.8	m	Sag middle beam	s	1/2*L_eff*θ	0.240883547	m
Height of beam	h	360	mm	0.36	m	curvature	κ	θ/h	0.26343345	m^-1
Width of beam	b	170	mm	0.17	m	strain	ε	κ*1/2*h*100%	4.741802102	%
thickness of body	t_b	8	mm	0.008	m					
thickness of flange	t_f	12.7	mm	0.0127	m				Generated force	
Area	A_s_beam	72.73	cm^2	0.007273	m^2	Impact force	F	E_impact/s*1.5	871790.5512	N
Moment of inertia y	I_y	16270	cm^4	0.0001627	m^4		F		871.7905512	kN
Section modulus y	W_y	904	cm^3	0.000904	m^3					
Moment of inertia z	I_z	1043	cm^4	0.00001043	m^4				Buckling of column	
Section modulus Z	W_z	123	cm^3	0.000123	m^3	Total height column	H_tot	H+s+0.2	4.440883547	m
Torsion resistance	I_t	373209.277	mm^3	3.73209E-07	m^3	Buckling capacity column	F_buck	(π^2*E*I_z) / (2*H_tot)^2	1960013.698	N
Warping resistance	I_w	3.1358E+11	mm^6	3.1358E-07	m^6	Buckling capacity column	F_buck		1960.013698	kN
k coefficient flange	k_f	0.43	-	0.43	-					
k coefficient body	k_b	4	-	4	-				Plate Buckling of beam	
						Plate flange stress capacity	σ_cr_plate_f	(k_f*π^2*E) / (12*(1-v^2)*(b/t_f)^2)	455485395.5	N/m^2
	Type of column					Plate flange Force capacity	F_cr_plate_f	(σ_cr_plate_f*b*t_f) / 1000	983.3929689	kN
	RHS 250x250x8									
Column height	H	4	m	4	m				Lateral Torsion Buckling of beam	
Height of beam	h_column	250	mm	0.25	m	Gravel lengte	L_g	L_g=L	5.8	m
Width of beam	b_column	250	mm	0.25	m	LTB moment capacity	M_cr	(π/L_g) * sqrt(E*I_z*G*I_t + ((π/L_g)^2)*E*I_z*E*I_w))	178286.5005	Nm
thickness of body	t_b_column	8	mm	0.008	m				178.2865005	kNm
thickness of flange	t_f_column	0	mm	0	m					
Area of column	A_column	76.8	cm^2	0.00768	m^2				Material use of DOPS	
Moment of inertia y	I_y_column	7460	cm^4	0.0000746	m^4	Material of 1 unit	m_tot	(2*A_p_beam*L_p+4*A_s_beam*L_s_beam+4*A_column*H_tot)*ρ	2713.731989	kg
Section modulus y	W_y_column	596	cm^3	0.000596	m^3	material of 1 meter DOPS	m _meter	m_tot/2.4	1130.721662	kg/m
Moment of inertia z	I_z_column	7460	cm^4	0.0000746	m^4					
Section modulus Z	W_z_column	596	cm^3	0.000596	m^3					
	Dropped Object									
	Sludge disposal Tank									
Dropped object energy	E_dropped object	300	kJ	300000	J					
Amount of beams hit	n	3	-	3	-					
factor	γ	1.4	-	1.4	-					

	Type of Steel		Original Unit		Converted Unit				Formula		Unit
	S355									Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))	80769230769	N/m^2
E-modulus	E	210000	N/mm^2	2.1E+11	N/m^2					
Poissons ratio	v	0.3	-	0.3	-				Plastic Moment Capacity	
density	ρ	7850	kg/m^3	7850	kg/m^3	Plastic moment capacity	M_pl	f_y*α*W_y	227395.25	Nm
							M_pl		227.39525	kNm
	Type of Primary Beam									
	IPE 360								Impact Energy	
length	L_p	2.4	m	2.4	m	Distribution Factor	β	(1/(n))*γ	0.466666667	-
Area	A_p_beam	72.73	cm^2	0.007273	m^2	impact energy	E_impact	E_dropped object*β	140000	j=Nm
	Type of Secondary Beam								Deformations	
	IPE 300					Effective length beam	L_eff	L-2*h	5.2	
Shape Factor	α	1.15	-	1.15	-	angle of bending	θ	(E_impact)/(4*M_pl)	0.153917023	-
Span	L_s	5.8	m	5.8	m	Sag middle beam	s	1/2*L_eff*θ	0.400184261	m
Height of beam	h	300	mm	0.3	m	curvature	κ	θ/h	0.513056744	m^-1
Width of beam	b	150	mm	0.15	m	strain	ε	κ*1/2*h*100%	7.695851167	%
thickness of body	t_b	7.1	mm	0.0071	m					
thickness of flange	t_f	10.7	mm	0.0107	m				Generated force	
Area	A_s_beam	53.81	cm^2	0.005381	m^2	Impact force	F	E_impact/s*1.5	524758.2692	N
Moment of inertia y	I_y	8360	cm^4	0.0000836	m^4		F		524.7582692	kN
Section modulus y	W_y	557	cm^3	0.000557	m^3					
Moment of inertia z	I_z	603.8	cm^4	0.000006038	m^4				Buckling of column	
Section modulus Z	W_z	80.5	cm^3	0.0000805	m^3	Total height column	H_tot	H+s+0.2	4.600184261	m
Torsion resistance	I_t	201184.9578	mm^3	2.01185E-07	m^3	Buckling capacity column	F_buck	(π^2*E*I_z) / (2*H_tot)^2	908411.2478	N
Warping resistance	I_w	1.25934E+11	mm^6	1.25934E-07	m^6	Buckling capacity column	F_buck		908.4112478	kN
k coefficient flange	k_f	0.43	-	0.43	-					
k coefficient body	k_b	4	-	4	-				Plate Buckling of beam	
						Plate flange stress capacity	σ_cr_plate_f	(k_f*π^2*E) / (12*(1-v^2)*(b/t_f)^2)	415288490.1	N/m^2
	Type of column					Plate flange Force capacity	F_cr_plate_f	(σ_cr_plate_f*b*t_f) / 1000	666.5380266	kN
	RHS 200x200x8									
Column height	H	4	m	4	m				Lateral Torsion Buckling of beam	
Height of beam	h_column	200	mm	0.2	m	Gravel lengte	L_g	L_g=L	5.8	m
Width of beam	b_column	200	mm	0.2	m	LTB moment capacity	M_cr	(π/L_g) * sqrt(E*I_z*G*I_t + ((π/L_g)^2)*E*I_z*E*I_w))	94506.38763	Nm
thickness of body	t_b_column	8	mm	0.008	m				94.50638763	kNm
thickness of flange	t_f_column	0	mm	0	m					
Area of column	A_column	60.8	cm^2	0.00608	m^2				Material use of DOPS	
Moment of inertia y	I_y_column	3710	cm^4	0.0000371	m^4	Material of 1 unit	m_tot	(2*A_p_beam*L_p+4*A_s_beam*L_s_beam+4*A_column*H_tot)*ρ	2132.264738	kg
Section modulus y	W_y_column	371	cm^3	0.000371	m^3	material of 1 meter DOPS	m _meter	m_tot/2.4	888.4436407	kg/m
Moment of inertia z	I_z_column	3710	cm^4	0.0000371	m^4					
Section modulus Z	W_z_column	371	cm^3	0.000371	m^3					
	Dropped Object									
	Sludge disposal Tank									
Dropped object energy	E_dropped object	300	kJ	300000	J					
Amount of beams hit	n	3	-	3	-					
factor	γ	1.4	-	1.4	-					

Appendix G: Calculations variant 3

Calculations of variant 3 without steel plate:

	Type of Steel		Original Unit		Converted Unit				Formula		Unit
	S355									Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))	80769230769	N/m^2
E-modulus	E	210000	N/mm^2	2.1E+11	N/m^2					
Poissons ratio	v	0.3	-	0.3	-				Plastic Moment Capacity	
density	ρ	7850	kg/m^3	7850	kg/m^3	Plastic moment capacity	M_pl	f_y*α*W_y	511200	Nm
							M_pl		511.2	kNm
	Type of Beam									
	RHS 400x200x10								Impact Energy	
Shape Factor	α	1.2	-	1.2	-	Distribution Factor	β	(1/(n))*γ	0.7	-
Span	L_s	5.8	m	5.8	m	impact energy	E_impact	E_dropped object*β	210000	j=Nm
Height of beam	h	400	mm	0.4	m					
Width of beam	b	200	mm	0.2	m				Deformations	
thickness	t	10	mm	0.01	m	Effective length beam	L_eff	L-2*h	5	
Area	A_s_beam	115	cm^2	0.0115	m^2	angle of bending	θ	(E_impact)/(4*M_pl)	0.102699531	-
Moment of inertia y	I_y	23900	cm^4	0.000239	m^4	Sag middle beam	s	1/2*L_eff*θ	0.256748826	m
Section modulus y	W_y	1200	cm^3	0.0012	m^3	curvature	κ	θ/h	0.256748826	m^-1
Moment of inertia z	I_z	8080	cm^4	0.0000808	m^4	strain	ε	κ*1/2*h*100%	5.134976526	%
Section modulus Z	W_z	808	cm^3	0.000808	m^3					
k coefficient flange	k_f	4	-	4	-				Generated force	
k coefficient body	k_b	4	-	4	-	Impact force	F	E_impact/s*1.5	1226880	N
							F		1226.88	kN
	Type of column									
	HEA 400								Buckling of column	
Column height	H	4	m	4	m	Total height column	H_tot	H+s+0.2	4.456748826	m
Height of beam	h_column	390	mm	0.39	m	Buckling capacity column	F_buck	(π^2*E*I_z) / (2*H_tot)^2	2234083.442	N
Width of beam	b_column	300	mm	0.3	m	Buckling capacity column	F_buck		2234.083442	kN
thickness of body	t_b_column	11	mm	0.011	m					
thickness of flange	t_f_column	19	mm	0.019	m				Plate Buckling of beam	
Area of column	A_column	159	cm^2	0.0159	m^2	Plate flange stress capacity	σ_cr_plate_f	(k_f*π^2*E) / (12*(1-v^2)*(b/t)^2)	1898000846	N/m^2
Moment of inertia y	I_y_column	45069	cm^4	0.00045069	m^4	Plate flange Force capacity	F_cr_plate_f	(σ_cr_plate_f*b*t) / 1000	3796.001693	kN
Section modulus y	W_y_column	2310	cm^3	0.00231	m^3					
Moment of inertia z	I_z_column	8564	cm^4	0.00008564	m^4				Material use of DOPS	
Section modulus Z	W_z_column	571	cm^3	0.000571	m^3	Material of 1 unit	m_tot	(L*A_beam+2*H_tot*A_column+2*A_beam)*ρ	1816.68321	kg
	Dropped Object									
	Sludge disposal Tank									
Dropped object energy	E_dropped object	300	kJ	300000	J					
Amount of beams hit	n	2	-	2	-					
factor	γ	1.4	-	1.4	-					

	Type of Steel		Original Unit		Converted Unit				Formula		Unit
	S355									Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))	80769230769	N/m^2
E-modulus	E	210000	N/mm^2	2.1E+11	N/m^2					
Poissons ratio	v	0.3	-	0.3	-				Plastic Moment Capacity	
density	ρ	7850	kg/m^3	7850	kg/m^3	Plastic moment capacity	M_pl	f_y*α*W_y	335688	Nm
							M_pl		335.688	kNm
	Type of Beam									
	RHS 300x200x10								Impact Energy	
Shape Factor	α	1.2	-	1.2	-	Distribution Factor	β	(1/(n))*γ	0.7	-
Span	L_s	5.8	m	5.8	m	impact energy	E_impact	E_dropped object*β	210000	j=Nm
Height of beam	h	300	mm	0.3	m					
Width of beam	b	200	mm	0.2	m				Deformations	
thickness	t	10	mm	0.01	m	Effective length beam	L_eff	L-2*h	5.2	
Area	A_s_beam	94.9	cm^2	0.00949	m^2	angle of bending	θ	(E_impact)/(4*M_pl)	0.156395224	-
Moment of inertia y	I_y	11800	cm^4	0.000118	m^4	Sag middle beam	s	1/2*L_eff*θ	0.406627583	m
Section modulus y	W_y	788	cm^3	0.000788	m^3	curvature	κ	θ/h	0.521317414	m^-1
Moment of inertia z	I_z	6280	cm^4	0.0000628	m^4	strain	ε	κ*1/2*h*100%	7.819761207	%
Section modulus Z	W_z	628	cm^3	0.000628	m^3					
k coefficient flange	k_f	4	-	4	-				Generated force	
k coefficient body	k_b	4	-	4	-	Impact force	F	E_impact/s*1.5	774664.6154	N
							F		774.6646154	kN
	Type of column									
	HEB 400								Buckling of column	
Column height	H	4	m	4	m	Total height column	H_tot	H+s+0.2	4.606627583	m
Height of beam	h_column	400	mm	0.4	m	Buckling capacity column	F_buck	(π^2*E*I_z) / (2*H_tot)^2	2641678.504	N
Width of beam	b_column	300	mm	0.3	m	Buckling capacity column	F_buck		2641.678504	kN
thickness of body	t_b_column	13.5	mm	0.0135	m					
thickness of flange	t_f_column	24	mm	0.024	m				Plate Buckling of beam	
Area of column	A_column	197.8	cm^2	0.01978	m^2	Plate flange stress capacity	σ_cr_plate_f	(k_f*π^2*E) / (12*(1-v^2)*(b/t)^2)	1898000846	N/m^2
Moment of inertia y	I_y_column	57680	cm^4	0.0005768	m^4	Plate flange Force capacity	F_cr_plate_f	(σ_cr_plate_f*b*t) / 1000	3796.001693	kN
Section modulus y	W_y_column	2880	cm^3	0.00288	m^3					
Moment of inertia z	I_z_column	10819	cm^4	0.00010819	m^4				Material use of DOPS	
Section modulus Z	W_z_column	721	cm^3	0.000721	m^3	Material of 1 unit	m_tot	(L*A_beam+2*H_tot*A_column+2*A_beam)*ρ	2011.642469	kg
	Dropped Object									
	Sludge disposal Tank									
Dropped object energy	E_dropped object	300	kJ	300000	J					
Amount of beams hit	n	2	-	2	-					
factor	γ	1.4	-	1.4	-					

	Type of Steel		Original Unit		Converted Unit				Formula		Unit
	S355									Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))	80769230769	N/m^2
E-modulus	E	210000	N/mm^2	2.1E+11	N/m^2					
Poissons ratio	v	0.3	-	0.3	-				Plastic Moment Capacity	
density	ρ	7850	kg/m^3	7850	kg/m^3	Plastic moment capacity	M_pl	f_y*α*W_y	276048	Nm
							M_pl		276.048	kNm
	Type of Beam									
	RHS 300x200x8								Impact Energy	
Shape Factor	α	1.2	-	1.2	-	Distribution Factor	β	(1/(n))*γ	0.7	-
Span	L_s	5.8	m	5.8	m	impact energy	E_impact	E_dropped object*β	210000	j=Nm
Height of beam	h	300	mm	0.3	m					
Width of beam	b	200	mm	0.2	m				Deformations	
thickness	t	8	mm	0.008	m	Effective length beam	L_eff	L-2*h	5.2	
Area	A_s_beam	76.8	cm^2	0.00768	m^2	angle of bending	θ	(E_impact)/(4*M_pl)	0.190184316	-
Moment of inertia y	I_y	9720	cm^4	0.0000972	m^4	Sag middle beam	s	1/2*L_eff*θ	0.494479221	m
Section modulus y	W_y	648	cm^3	0.000648	m^3	curvature	κ	θ/h	0.633947719	m^-1
Moment of inertia z	I_z	5180	cm^4	0.0000518	m^4	strain	ε	κ*1/2*h*100%	9.509215789	%
Section modulus Z	W_z	518	cm^3	0.000518	m^3					
k coefficient flange	k_f	4	-	4	-				Generated force	
k coefficient body	k_b	4	-	4	-	Impact force	F	E_impact/s*1.5	637033.8462	N
							F		637.0338462	kN
	Type of column									
	HEB 300								Buckling of column	
Column height	H	4	m	4	m	Total height column	H_tot	H+s+0.2	4.694479221	m
Height of beam	h_column	300	mm	0.3	m	Buckling capacity column	F_buck	(π^2*E*I_z) / (2*H_tot)^2	2013307.682	N
Width of beam	b_column	300	mm	0.3	m	Buckling capacity column	F_buck		2013.307682	kN
thickness of body	t_b_column	11	mm	0.011	m					
thickness of flange	t_f_column	19	mm	0.019	m				Plate Buckling of beam	
Area of column	A_column	149.1	cm^2	0.01491	m^2	Plate flange stress capacity	σ_cr_plate_f	(k_f*π^2*E) / (12*(1-v^2)*(b/t)^2)	1214720542	N/m^2
Moment of inertia y	I_y_column	25166	cm^4	0.00025166	m^4	Plate flange Force capacity	F_cr_plate_f	(σ_cr_plate_f*b*t) / 1000	1943.552867	kN
Section modulus y	W_y_column	1680	cm^3	0.00168	m^3					
Moment of inertia z	I_z_column	8563	cm^4	0.00008563	m^4				Material use of DOPS	
Section modulus Z	W_z_column	571	cm^3	0.000571	m^3	Material of 1 unit	m_tot	(L*A_beam+2*H_tot*A_column+2*A_beam)*ρ	1569.162957	kg
	Dropped Object									
	Sludge disposal Tank									
Dropped object energy	E_dropped object	300	kJ	300000	J					
Amount of beams hit	n	2	-	2	-					
factor	γ	1.4	-	1.4	-					

	Type of Steel		Original Unit		Converted Unit				Formula		Unit
	S355									Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))	80769230769	N/m^2
E-modulus	E	210000	N/mm^2	2.1E+11	N/m^2					
Poissons ratio	v	0.3	-	0.3	-				Plastic Moment Capacity	
density	ρ	7850	kg/m^3	7850	kg/m^3	Plastic moment capacity	M_pl	f_y*α*W_y	210444	Nm
							M_pl		210.444	kNm
	Type of Beam									
	RHS 250x150x10								Impact Energy	
Shape Factor	α	1.2	-	1.2	-	Distribution Factor	β	(1/(n))*γ	0.7	-
Span	L_s	5.8	m	5.8	m	impact energy	E_impact	E_dropped object*β	210000	j=Nm
Height of beam	h	250	mm	0.25	m					
Width of beam	b	150	mm	0.15	m				Deformations	
thickness	t	10	mm	0.01	m	Effective length beam	L_eff	L-2*h	5.3	
Area	A_s_beam	74.9	cm^2	0.00749	m^2	angle of bending	θ	(E_impact)/(4*M_pl)	0.249472544	-
Moment of inertia y	I_y	6170	cm^4	0.0000617	m^4	Sag middle beam	s	1/2*L_eff*θ	0.661102241	m
Section modulus y	W_y	494	cm^3	0.000494	m^3	curvature	κ	θ/h	0.997890175	m^-1
Moment of inertia z	I_z	2760	cm^4	0.0000276	m^4	strain	ε	κ*1/2*h*100%	12.47362719	%
Section modulus Z	W_z	367	cm^3	0.000367	m^3					
k coefficient flange	k_f	4	-	4	-				Generated force	
k coefficient body	k_b	4	-	4	-	Impact force	F	E_impact/s*1.5	476476.9811	N
							F		476.4769811	kN
	Type of column									
	HEA 300								Buckling of column	
Column height	H	4	m	4	m	Total height column	H_tot	H+s+0.2	4.861102241	m
Height of beam	h_column	290	mm	0.29	m	Buckling capacity column	F_buck	(π^2*E*I_z) / (2*H_tot)^2	1383626.582	N
Width of beam	b_column	300	mm	0.3	m	Buckling capacity column	F_buck		1383.626582	kN
thickness of body	t_b_column	8.5	mm	0.0085	m					
thickness of flange	t_f_column	14	mm	0.014	m				Plate Buckling of beam	
Area of column	A_column	112.5	cm^2	0.01125	m^2	Plate flange stress capacity	σ_cr_plate_f	(k_f*π^2*E) / (12*(1-v^2)*(b/t)^2)	3374223727	N/m^2
Moment of inertia y	I_y_column	18263	cm^4	0.00018263	m^4	Plate flange Force capacity	F_cr_plate_f	(σ_cr_plate_f*b*t) / 1000	5061.33559	kN
Section modulus y	W_y_column	1260	cm^3	0.00126	m^3					
Moment of inertia z	I_z_column	6310	cm^4	0.0000631	m^4				Material use of DOPS	
Section modulus Z	W_z_column	421	cm^3	0.000421	m^3	Material of 1 unit	m_tot	(L*A_beam+2*H_tot*A_column+2*A_beam)*ρ	1317.204883	kg
	Dropped Object									
	Sludge disposal Tank									
Dropped object energy	E_dropped object	300	kJ	300000	J					
Amount of beams hit	n	2	-	2	-					
factor	γ	1.4	-	1.4	-					

Calculations of variant 3 with steel plate:

	Type of Steel		Original Unit		Converted Unit				Formula		Unit
	S355									Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))	80769230769	N/m^2	
E-modulus	E	210000	N/mm^2	2.1E+11	N/m^2						
Poissons ratio	v	0.3	-	0.3	-				Impact Energy		
density	ρ	7850	kg/m^3	7850	kg/m^3	Distribution Factor	β	(1/(n))*γ	0.7	-	
						impact energy	E_impact	E_dropped object*β	210000	j=Nm	
	Type of Beam										
	RHS 400x200x10								Centre of gravity		
Span	L	5.8	m	5.8	m	Area plate	A_p	t_p*L_p	0.1	m^2	
Height of beam	h	400	mm	0.4	m	Area beam	A_b	b*h-(b-2*t)*(h-2*t)	0.0116	m^2	
Width of beam	b	200	mm	0.2	m	Total Area	A_tot	A_p+A_b	0.1116	m^2	
thickness	t	10	mm	0.01	m	centre of gravity	y_cg	(A_p*1/2*t_p+A_b*(t_p+1/2*h))/(A_p+A_b)	0.075985663	m	
Area	A_beam	115	cm^2	0.0115	m^2						
									Moment of inertia		
	Type Plate					Moment of inertia of plate new	I_y_plate	1/12*L_p*t_p^3+(L_p*t_p)*(y_cg-1/2*t_p)^2	0.000150859	m^4	
thickness plate	t_p	100	mm	0.1	m	Moment of inertia of beam new	I_y_beam	(1/12*b*h^3+(b*h)*(t_p+1/2*h-y_cg))-(1/12*(b-2t)*(h-2t)^3+(b-2t)*(h-2t)*(t_p+1/2*h-y_cg)^2	0.000825703	m^4	
length of plate	L_p	1000	mm	1	m	Moment of inertia	I_y	I_y_plate + I_y_beam	0.000976562	m^4	
	Type of column								Plastic moment capacity		
	HEA 400					neutral axis	y_na	(A_tot/2)/L_p	0.0558	m	
Column height	H	4	m	4	m	Force in plate above na	F_plate_above_na	A_above*f_y	19809	kN	
Height of beam	h_column	390	mm	0.39	m	Force in plate below na	F_plate_below_na	A_below*f_y	15691	kN	
Width of beam	b_column	300	mm	0.3	m	Force in RHS	F_RHS	A_b*f_y	4118	kN	
thickness of body	t_b_column	11	mm	0.011	m	plastic moment capacity	M_pl	plastic moment capacity	1905.0578	kNm	
thickness of flange	t_f_column	19	mm	0.019	m		M_pl		1905057.8	Nm	
Area of column	A_column	159	cm^2	0.0159	m^2						
Moment of inertia y	I_y_column	45069	cm^4	0.00045069	m^4				Deformations		
Section modulus y	W_y_column	2310	cm^3	0.00231	m^3	Effective length beam	L_eff	L-2*(h+t_p)	4.8		
Moment of inertia z	I_z_column	8564	cm^4	0.00008564	m^4	angle of bending	θ	(E_impact)/(4*M_pl)	0.027558219	-	
Section modulus Z	W_z_column	571	cm^3	0.000571	m^3	Sag middle beam	s	1/2*L_eff*θ	0.066139726	m	
						curvature	κ	θ/h	0.0706621	m^-1	
	Dropped Object					strain	ε	κ*1/2*h*100%	1.377910948	%	
	Sludge disposal Tank										
Dropped object energy	E_dropped object	300	kJ	300000	J						
Amount of beams hit	n	2	-	2	-				Generated force		
factor	γ	1.4	-	1.4	-	Impact force	F	E_impact/s*1.5	4762644.5	N	
							F		4762.6445	kN	
									Weight		
						Material of 1 meter of DOPS	m_tot	(L*A_beam+2*H_tot*A_column+2*A_beam+L*t_p)*ρ	6075.115	kg	

	Type of Steel		Original Unit		Converted Unit				Formula		Unit
	S355									Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))	80769230769	N/m^2	
E-modulus	E	210000	N/mm^2	2.1E+11	N/m^2						
Poissons ratio	v	0.3	-	0.3	-				Impact Energy		
density	ρ	7850	kg/m^3	7850	kg/m^3	Distribution Factor	β	(1/(n))*γ	0.7	-	
						impact energy	E_impact	E_dropped object*β	210000	j=Nm	
	Type of Beam										
	RHS 300x200x10								Centre of gravity		
Span	L	5.8	m	5.8	m	Area plate	A_p	t_p*L_p	0.1	m^2	
Height of beam	h	300	mm	0.3	m	Area beam	A_b	b*h-(b-2*t)*(h-2*t)	0.0096	m^2	
Width of beam	b	200	mm	0.2	m	Total Area	A_tot	A_p+A_b	0.1096	m^2	
thickness	t	10	mm	0.01	m	centre of gravity	y_cg	(A_p*1/2*t_p+A_b*(t_p+1/2*h))/(A_p+A_b)	0.067518248	m	
Area	A_beam	94.9	cm^2	0.00949	m^2						
									Moment of inertia		
	Type Plate					Moment of inertia of plate new	I_y_plate	1/12*L_p*t_p^3+(L_p*t_p)*(y_cg-1/2*t_p)^2	0.000114022	m^4	
thickness plate	t_p	100	mm	0.1	m	Moment of inertia of beam new	I_y_beam	(1/12*b*h^3+(b*h)*(t_p+1/2*h-y_cg))-(1/12*(b-2t)*(h-2t)^3+(b-2t)*(h-2t)*(t_p+1/2*h-y_cg)^2	0.000440396	m^4	
length of plate	L_p	1000	mm	1	m	Moment of inertia	I_y	I_y_plate + I_y_beam	0.000554418	m^4	
	Type of column								Plastic moment capacity		
	HEA 400					neutral axis	y_na	(A_tot/2)/L_p	0.0548	m	
Column height	H	4	m	4	m	Force in plate above na	F_plate_above_na	A_above*f_y	19454	kN	
Height of beam	h_column	390	mm	0.39	m	Force in plate below na	F_plate_below_na	A_below*f_y	16046	kN	
Width of beam	b_column	300	mm	0.3	m	Force in RHS	F_RHS	A_b*f_y	3408	kN	
thickness of body	t_b_column	11	mm	0.011	m	plastic moment capacity	M_pl	plastic moment capacity	1560.9208	kNm	
thickness of flange	t_f_column	19	mm	0.019	m		M_pl		1560920.8	Nm	
Area of column	A_column	159	cm^2	0.0159	m^2						
Moment of inertia y	I_y_column	45069	cm^4	0.00045069	m^4				Deformations		
Section modulus y	W_y_column	2310	cm^3	0.00231	m^3	Effective length beam	L_eff	L-2*(h+t_p)	5		
Moment of inertia z	I_z_column	8564	cm^4	0.00008564	m^4	angle of bending	θ	(E_impact)/(4*M_pl)	0.033633993	-	
Section modulus Z	W_z_column	571	cm^3	0.000571	m^3	Sag middle beam	s	1/2*L_eff*θ	0.084084984	m	
						curvature	κ	θ/h	0.086241009	m^-1	
	Dropped Object					strain	ε	κ*1/2*h*100%	1.681699674	%	
	Sludge disposal Tank										
Dropped object energy	E_dropped object	300	kJ	300000	J						
Amount of beams hit	n	2	-	2	-				Generated force		
factor	γ	1.4	-	1.4	-	Impact force	F	E_impact/s*1.5	3746209.92	N	
							F		3746.20992	kN	
									Weight		
						Material of 1 meter of DOPS	m_tot	(L*A_beam+2*H_tot*A_column+2*A_beam+L*t_p)*ρ	5983.5997	kg	

	Type of Steel		Original Unit		Converted Unit				Formula		Unit
	S355									Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))	80769230769	N/m^2	
E-modulus	E	210000	N/mm^2	2.1E+11	N/m^2						
Poissons ratio	v	0.3	-	0.3	-				Impact Energy		
density	ρ	7850	kg/m^3	7850	kg/m^3	Distribution Factor	β	(1/(n))*γ	0.7	-	
						impact energy	E_impact	E_dropped object*β	210000	j=Nm	
	Type of Beam										
	RHS 300x200x8								Centre of gravity		
Span	L	5.8	m	5.8	m	Area plate	A_p	t_p*L_p	0.05	m^2	
Height of beam	h	300	mm	0.3	m	Area beam	A_b	b*h-(b-2*t)*(h-2*t)	0.007744	m^2	
Width of beam	b	200	mm	0.2	m	Total Area	A_tot	A_p+A_b	0.057744	m^2	
thickness	t	8	mm	0.008	m	centre of gravity	y_cg	(A_p*1/2*t_p+A_b*(t_p+1/2*h))/(A_p+A_b)	0.048469105	m	
Area	A_beam	76.8	cm^2	0.00768	m^2						
									Moment of inertia		
	Type Plate					Moment of inertia of plate new	I_y_plate	1/12*L_p*t_p^3+(L_p*t_p)*(y_cg-1/2*t_p)^2	3.79566E-05	m^4	
thickness plate	t_p	50	mm	0.05	m	Moment of inertia of beam new	I_y_beam	(1/12*b*h^3+(b*h)*(t_p+1/2*h-y_cg))-(1/12*(b-2t)*(h-2t)^3+(b-2t)*(h-2t)*(t_p+1/2*h-y_cg)^2	0.000276585	m^4	
length of plate	L_p	1000	mm	1	m	Moment of inertia	I_y	I_y_plate + I_y_beam	0.000314541	m^4	

	Type of column									Plastic moment capacity	
	HEA 400					neutral axis	y_na	(A_tot/2)/L_p		0.028872	m
Column height	H	4	m	4	m	Force in plate above na	F_plate_above_na	A_above*f_y		10249.56	kN
Height of beam	h_column	390	mm	0.39	m	Force in plate below na	F_plate_below_na	A_below*f_y		7500.44	kN
Width of beam	b_column	300	mm	0.3	m	Force in RHS	F_RHS	A_b*f_y		2749.12	kN
thickness of body	t_b_column	11	mm	0.011	m	plastic moment capacity	M_pl	plastic moment capacity		697.6487037	kNm
thickness of flange	t_f_column	19	mm	0.019	m		M_pl			697648.7037	Nm
Area of column	A_column	159	cm^2	0.0159	m^2						
Moment of inertia y	I_y_column	45069	cm^4	0.00045069	m^4					Deformations	
Section modulus y	W_y_column	2310	cm^3	0.00231	m^3	Effective length beam	L_eff	L-2*(h+t_p)		5.1	
Moment of inertia z	I_z_column	8564	cm^4	0.00008564	m^4	angle of bending	θ	(E_impact)/(4*M_pl)		0.075252774	-
Section modulus Z	W_z_column	571	cm^3	0.000571	m^3	Sag middle beam	s	1/2*L_eff*θ		0.191894573	m
						curvature	κ	θ/h		0.19295583	m^-1
	Dropped Object					strain	ε	κ*1/2*h*100%		3.762638684	%
	Sludge disposal Tank										
Dropped object energy	E_dropped object	300	kJ	300000	J						
Amount of beams hit	n	2	-	2	-					Generated force	
factor	γ	1.4	-	1.4	-	Impact force	F	E_impact/s*1.5		1641526.362	N
							F			1641.526362	kN
										Weight	
						Material of 1 meter of DOPS	m_tot	(L*A_beam+2*H_tot*A_column+2*A_beam+L*t_p)*ρ		3624.6904	kg

	Type of Steel		Original Unit		Converted Unit			Formula		Unit
	S355								Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))	80769230769	N/m^2
E-modulus	E	210000	N/mm^2	2.1E+11	N/m^2					
Poissons ratio	v	0.3	-	0.3	-				Impact Energy	
density	ρ	7850	kg/m^3	7850	kg/m^3	Distribution Factor	β	(1/(n))*γ	0.7	-
						impact energy	E_impact	E_dropped object*β	210000	j=Nm
	Type of Beam									
	RHS 300x100x10								Centre of gravity	
Span	L	5.8	m	5.8	m	Area plate	A_p	t_p*L_p	0.05	m^2
Height of beam	h	300	mm	0.3	m	Area beam	A_b	b*h-(b-2*t)*(h-2*t)	0.0076	m^2
Width of beam	b	100	mm	0.1	m	Total Area	A_tot	A_p+A_b	0.0576	m^2
thickness	t	10	mm	0.01	m	centre of gravity	y_cg	(A_p*1/2*t_p+A_b*(t_p+1/2*h))/(A_p+A_b)	0.048090278	m
Area	A_beam	74.9	cm^2	0.00749	m^2					
									Moment of inertia	
	Type Plate					Moment of inertia of plate new	I_y_plate	1/12*L_p*t_p^3+(L_p*t_p)*(y_cg-1/2*t_p)^2	3.70747E-05	m^4
thickness plate	t_p	50	mm	0.05	m	Moment of inertia of beam new	I_y_beam	(1/12*b*h^3+(b*h)*(t_p+1/2*h-y_cg))-(1/12*(b-2t)*(h-2t)^3+(b-2t)*(h-2t)*(t_p+1/2*h-y_cg)^2	0.000254035	m^4
length of plate	L_p	1000	mm	1	m	Moment of inertia	I_y	I_y_plate + I_y_beam	0.00029111	m^4
	Type of column								Plastic moment capacity	
	HEA 400					neutral axis	y_na	(A_tot/2)/L_p	0.0288	m
Column height	H	4	m	4	m	Force in plate above na	F_plate_above_na	A_above*f_y	10224	kN
Height of beam	h_column	390	mm	0.39	m	Force in plate below na	F_plate_below_na	A_below*f_y	7526	kN
Width of beam	b_column	300	mm	0.3	m	Force in RHS	F_RHS	A_b*f_y	2698	kN
thickness of body	t_b_column	11	mm	0.011	m	plastic moment capacity	M_pl	plastic moment capacity	688.8988	kNm
thickness of flange	t_f_column	19	mm	0.019	m		M_pl		688898.8	Nm
Area of column	A_column	159	cm^2	0.0159	m^2					
Moment of inertia y	I_y_column	45069	cm^4	0.00045069	m^4				Deformations	
Section modulus y	W_y_column	2310	cm^3	0.00231	m^3	Effective length beam	L_eff	L-2*(h+t_p)	5.1	
Moment of inertia z	I_z_column	8564	cm^4	0.00008564	m^4	angle of bending	θ	(E_impact)/(4*M_pl)	0.076208581	-
Section modulus Z	W_z_column	571	cm^3	0.000571	m^3	Sag middle beam	s	1/2*L_eff*θ	0.194331882	m
						curvature	κ	θ/h	0.195406618	m^-1
	Dropped Object					strain	ε	κ*1/2*h*100%	3.81042905	%
	Sludge disposal Tank									
Dropped object energy	E_dropped object	300	kJ	300000	J					
Amount of beams hit	n	2	-	2	-				Generated force	
factor	γ	1.4	-	1.4	-	Impact force	F	E_impact/s*1.5	1620938.353	N
							F		1620.938353	kN
									Weight	
						Material of 1 meter of DOPS	m_tot	(L*A_beam+2*H_tot*A_column+2*A_beam+L*t_p)*ρ	3616.0397	kg

	Type of Steel		Original Unit		Converted Unit			Formula		Unit
	S355								Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))	80769230769	N/m^2
E-modulus	E	210000	N/mm^2	2.1E+11	N/m^2					
Poissons ratio	v	0.3	-	0.3	-				Impact Energy	
density	ρ	7850	kg/m^3	7850	kg/m^3	Distribution Factor	β	(1/(n))*γ	0.7	-
						impact energy	E_impact	E_dropped object*β	210000	j=Nm
	Type of Beam									
	RHS 250x150x10								Centre of gravity	
Span	L	5.8	m	5.8	m	Area plate	A_p	t_p*L_p	0.025	m^2
Height of beam	h	250	mm	0.25	m	Area beam	A_b	b*h-(b-2*t)*(h-2*t)	0.0076	m^2
Width of beam	b	150	mm	0.15	m	Total Area	A_tot	A_p+A_b	0.0326	m^2
thickness	t	10	mm	0.01	m	centre of gravity	y_cg	(A_p*1/2*t_p+A_b*(t_p+1/2*h))/(A_p+A_b)	0.044555215	m
Area	A_beam	74.9	cm^2	0.00749	m^2					
									Moment of inertia	
	Type Plate					Moment of inertia of plate new	I_y_plate	1/12*L_p*t_p^3+(L_p*t_p)*(y_cg-1/2*t_p)^2	2.69905E-05	m^4
thickness plate	t_p	25	mm	0.025	m	Moment of inertia of beam new	I_y_beam	(1/12*b*h^3+(b*h)*(t_p+1/2*h-y_cg))-(1/12*(b-2t)*(h-2t)^3+(b-2t)*(h-2t)*(t_p+1/2*h-y_cg)^2	0.000148005	m^4
length of plate	L_p	1000	mm	1	m	Moment of inertia	I_y	I_y_plate + I_y_beam	0.000174995	m^4
	Type of column								Plastic moment capacity	
	HEA 400					neutral axis	y_na	(A_tot/2)/L_p	0.0163	m
Column height	H	4	m	4	m	Force in plate above na	F_plate_above_na	A_above*f_y	5786.5	kN
Height of beam	h_column	390	mm	0.39	m	Force in plate below na	F_plate_below_na	A_below*f_y	3088.5	kN
Width of beam	b_column	300	mm	0.3	m	Force in RHS	F_RHS	A_b*f_y	2698	kN
thickness of body	t_b_column	11	mm	0.011	m	plastic moment capacity	M_pl	plastic moment capacity	421.31755	kNm
thickness of flange	t_f_column	19	mm	0.019	m		M_pl		421317.55	Nm
Area of column	A_column	159	cm^2	0.0159	m^2					
Moment of inertia y	I_y_column	45069	cm^4	0.00045069	m^4				Deformations	
Section modulus y	W_y_column	2310	cm^3	0.00231	m^3	Effective length beam	L_eff	L-2*(h+t_p)	5.25	
Moment of inertia z	I_z_column	8564	cm^4	0.00008564	m^4	angle of bending	θ	(E_impact)/(4*M_pl)	0.124609098	-
Section modulus Z	W_z_column	571	cm^3	0.000571	m^3	Sag middle beam	s	1/2*L_eff*θ	0.327098883	m
						curvature	κ	θ/h	0.319510508	m^-1
	Dropped Object					strain	ε	κ*1/2*h*100%	6.230454915	%
	Sludge disposal Tank									
Dropped object energy	E_dropped object	300	kJ	300000	J					
Amount of beams hit	n	2	-	2	-				Generated force	
factor	γ	1.4	-	1.4	-	Impact force	F	E_impact/s*1.5	963011.5429	N
							F		963.0115429	kN
									Weight	
						Material of 1 meter of DOPS	m_tot	(L*A_beam+2*H_tot*A_column+2*A_beam+L*t_p)*ρ	2477.7897	kg

Appendix H: Calculations final variant

	Type of Steel		Original Unit		Converted Unit				Formula		Unit
	S355									Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))		80769230769	N/m^2
E-modulus	E	210000	N/mm^2	2,1E+11	N/m^2						
Poissons ratio	v	0,3	-	0,3	-					Plastic Moment Capacity	
density	ρ	7850	kg/m^3	7850	kg/m^3	Plastic moment capacity	M_pl	f_y*α*W_y		979800	Nm
							M_pl			979,8	kNm
	Type of Beam										
	HEB 360									Impact Energy	
Shape Factor	α	1,15	-	1,15	-	Distribution Factor	β	(1/(n))*γ		0,7	-
Span	L	5,8	m	5,8	m	impact energy	E_impact	E_dropped object*β		210000	j=Nm
Height of beam	h	360	mm	0,36	m						
Width of beam	b	300	mm	0,3	m					Deformations	
thickness of body	t_b	12,5	mm	0,0125	m	Effective length beam	L_eff	L-2*h		5,08	
thickness of flange	t_f	22,5	mm	0,0225	m	angle of bending	θ	(E_impact)/(4*M_pl)		0,053582364	-
Area	A_beam	180,6	cm^2	0,01806	m^2	Sag middle beam	s	1/2*L_eff*θ		0,136099204	m
Moment of inertia y	I_y	43193	cm^4	0,00043193	m^4	curvature	κ	θ/h		0,148839899	m^-1
Section modulus y	W_y	2400	cm^3	0,0024	m^3	strain	ε	κ*1/2*h*100%		2,679118187	%
Moment of inertia z	I_z	10141	cm^4	0,00010141	m^4						
Section modulus Z	W_z	676	cm^3	0,000676	m^3					Generated force	
Torsion resistance	I_t	2924527,957	mm^3	2,92453E-06	m^3	Impact force	F	E_impact/s*1.5		2314488,189	N
Warping resistance	I_w	2,88325E+12	mm^6	2,88325E-06	m^6		F			2314,488189	kN
k coefficient flange	k_f	0,43	-	0,43	-						
k coefficient body	k_b	4	-	4	-					Buckling of column	
						Total height column	H_tot	H+s+0.2		4,336099204	m
	Type of column					Buckling capacity column	F_buck	(π^2*E*I_z) / (2*H_tot)^2		2893676,174	N
	RHS 300x300x6.3					Buckling capacity column	F_buck			2893,676174	kN
Column height	H	4	m	4	m						
Height of beam	h_column	300	mm	0,3	m					Plate Buckling of beam	
Width of beam	b_column	300	mm	0,3	m	Plate flange stress capacity	σ_cr_plate_f	(k_f*π^2*E) / (12*(1-v^2)*(b/t_f)^2)		459078954,7	N/m^2
thickness of body	t_b_column	6,3	mm	0,0063	m	Plate flange Force capacity	F_cr_plate_f	(σ_cr_plate_f*b*t_f) / 1000		3098,782944	kN
thickness of flange	t_f_column	0	mm	0	m						
Area of column	A_column	73,6	cm^2	0,00736	m^2					Lateral Torsion Buckling of beam	
Moment of inertia y	I_y_column	10500	cm^4	0,000105	m^4	Gravel lengte	L_g	L_g=L		5,8	m
Section modulus y	W_y_column	703	cm^3	0,000703	m^3	LTB moment capacity	M_cr	(π/L_g) * sqrt(E*I_z*G*I_t + ((π/L_g)^2)*E*I_z*E*I_w))		1608034,746	Nm
Moment of inertia z	I_z_column	10500	cm^4	0,000105	m^4					1608,034746	kNm
Section modulus Z	W_z_column	703	cm^3	0,000703	m^3						
										Material use of DOPS	
	Dropped Object					Material used for one meter DOPS	m_tot	(L*A_beam+2*H_tot*A_column+2*A_beam)*ρ		1606,858735	kg
	Sludge disposal Tank										
Dropped object energy	E_dropped object	300	kJ	300000	J						
Amount of beams hit	n	2	-	2	-						
factor	γ	1,4	-	1,4	-						

	Type of Steel		Original Unit		Converted Unit				Formula		Unit
	S355									Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))		80769230769	N/m^2
E-modulus	E	210000	N/mm^2	2,1E+11	N/m^2						
Poissons ratio	v	0,3	-	0,3	-					Plastic Moment Capacity	
density	ρ	7850	kg/m^3	7850	kg/m^3	Plastic moment capacity	M_pl	f_y*α*W_y		881820	Nm
							M_pl			881,82	kNm
	Type of Beam										
	HEB 340									Impact Energy	
Shape Factor	α	1,15	-	1,15	-	Distribution Factor	β	(1/(n))*γ		0,7	-
Span	L	5,8	m	5,8	m	impact energy	E_impact	E_dropped object*β		210000	j=Nm
Height of beam	h	340	mm	0,34	m						
Width of beam	b	300	mm	0,3	m					Deformations	
thickness of body	t_b	12	mm	0,012	m	Effective length beam	L_eff	L-2*h		5,12	
thickness of flange	t_f	21,5	mm	0,0215	m	angle of bending	θ	(E_impact)/(4*M_pl)		0,05953596	-
Area	A_beam	170,9	cm^2	0,01709	m^2	Sag middle beam	s	1/2*L_eff*θ		0,152412057	m
Moment of inertia y	I_y	36656	cm^4	0,00036656	m^4	curvature	κ	θ/h		0,175105764	m^-1
Section modulus y	W_y	2160	cm^3	0,00216	m^3	strain	ε	κ*1/2*h*100%		2,976797986	%
Moment of inertia z	I_z	9690	cm^4	0,0000969	m^4						
Section modulus Z	W_z	646	cm^3	0,000646	m^3					Generated force	
Torsion resistance	I_t	2572042,615	mm^3	2,57204E-06	m^3	Impact force	F	E_impact/s*1.5		2066765,625	N
Warping resistance	I_w	2,45363E+12	mm^6	2,45363E-06	m^6		F			2066,765625	kN
k coefficient flange	k_f	0,43	-	0,43	-						
k coefficient body	k_b	4	-	4	-					Buckling of column	
						Total height column	H_tot	H+s+0.2		4,352412057	m
	Type of column					Buckling capacity column	F_buck	(π^2*E*I_z) / (2*H_tot)^2		2872025,81	N
	RHS 300x300x6.3					Buckling capacity column	F_buck			2872,02581	kN
Column height	H	4	m	4	m						
Height of beam	h_column	300	mm	0,3	m					Plate Buckling of beam	
Width of beam	b_column	300	mm	0,3	m	Plate flange stress capacity	σ_cr_plate_f	(k_f*π^2*E) / (12*(1-v^2)*(b/t_f)^2)		419178759,1	N/m^2
thickness of body	t_b_column	6,3	mm	0,0063	m	Plate flange Force capacity	F_cr_plate_f	(σ_cr_plate_f*b*t_f) / 1000		2703,702996	kN
thickness of flange	t_f_column	0	mm	0	m						
Area of column	A_column	73,6	cm^2	0,00736	m^2					Lateral Torsion Buckling of beam	
Moment of inertia y	I_y_column	10500	cm^4	0,000105	m^4	Gravel lengte	L_g	L_g=L		5,8	m
Section modulus y	W_y_column	703	cm^3	0,000703	m^3	LTB moment capacity	M_cr	(π/L_g) * sqrt(E*I_z*G*I_t + ((π/L_g)^2)*E*I_z*E*I_w))		1463824,065	Nm
Moment of inertia z	I_z_column	10500	cm^4	0,000105	m^4					1463,824065	kNm
Section modulus Z	W_z_column	703	cm^3	0,000703	m^3						
										Material use of DOPS	
	Dropped Object					Material used for one meter DOPS	m_tot	(L*A_beam+2*H_tot*A_column+2*A_beam)*ρ		1549,350618	kg
	Sludge disposal Tank										
Dropped object energy	E_dropped object	300	kJ	300000	J						
Amount of beams hit	n	2	-	2	-						
factor	γ	1,4	-	1,4	-						

	Type of Steel		Original Unit		Converted Unit				Formula		Unit
	S355									Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))		80769230769	N/m^2
E-modulus	E	210000	N/mm^2	2,1E+11	N/m^2						
Poissons ratio	v	0,3	-	0,3	-					Plastic Moment Capacity	
density	ρ	7850	kg/m^3	7850	kg/m^3	Plastic moment capacity	M_pl	f_y*α*W_y		787922,5	Nm
							M_pl			787,9225	kNm
	Type of Beam										
	HEB 320									Impact Energy	
Shape Factor	α	1,15	-	1,15	-	Distribution Factor	β	(1/(n))*γ		0,7	-
Span	L	5,8	m	5,8	m	impact energy	E_impact	E_dropped object*β		210000	j=Nm
Height of beam	h	320	mm	0,32	m						
Width of beam	b	300	mm	0,3	m					Deformations	
thickness of body	t_b	11,5	mm	0,0115	m	Effective length beam	L_eff	L-2*h		5,16	
thickness of flange	t_f	20,5	mm	0,0205	m	angle of bending	θ	(E_impact)/(4*M_pl)		0,066630919	-
Area	A_beam	161,3	cm^2	0,01613	m^2	Sag middle beam	s	1/2*L_eff*θ		0,17190777	m
Moment of inertia y	I_y	30823	cm^4	0,00030823	m^4	curvature	κ	θ/h		0,208221621	m^-1
Section modulus y	W_y	1930	cm^3	0,00193	m^3	strain	ε	κ*1/2*h*100%		3,331545932	%
Moment of inertia z	I_z	9239	cm^4	0,00009239	m^4						
Section modulus Z	W_z	616	cm^3	0,000616	m^3					Generated force	
Torsion resistance	I_t	2250692,611	mm^3	2,25069E-06	m^3	Impact force	F	E_impact/s*1.5		1832377,907	N
Warping resistance	I_w	2,06871E+12	mm^6	2,06871E-06	m^6		F			1832,377907	kN
k coefficient flange	k_f	0,43	-	0,43	-						
k coefficient body	k_b	4	-	4	-					Buckling of column	
						Total height column	H_tot	H+s+0.2		4,37190777	m
	Type of column					Buckling capacity column	F_buck	(π^2*E*I_z) / (2*H_tot)^2		2846468,387	N
	RHS 300x300x6.3					Buckling capacity column	F_buck			2846,468387	kN
Column height	H	4	m	4	m						
Height of beam	h_column	300	mm	0,3	m					Plate Buckling of beam	
Width of beam	b_column	300	mm	0,3	m	Plate flange stress capacity	σ_cr_plate_f	(k_f*π^2*E) / (12*(1-v^2)*(b/t_f)^2)		381092208,8	N/m^2
thickness of body	t_b_column	6,3	mm	0,0063	m	Plate flange Force capacity	F_cr_plate_f	(σ_cr_plate_f*b*t_f) / 1000		2343,717084	kN
thickness of flange	t_f_column	0	mm	0	m						
Area of column	A_column	73,6	cm^2	0,00736	m^2					Lateral Torsion Buckling of beam	
Moment of inertia y	I_y_column	10500	cm^4	0,000105	m^4	Gravel lengte	L_g	L_g=L		5,8	m
Section modulus y	W_y_column	703	cm^3	0,000703	m^3	LTB moment capacity	M_cr	(π/L_g) * sqrt(E*I_z*G*I_t + ((π/L_g)^2)*E*I_z*E*I_w))		1326765,971	Nm
Moment of inertia z	I_z_column	10500	cm^4	0,000105	m^4					1326,765971	kNm
Section modulus Z	W_z_column	703	cm^3	0,000703	m^3						
										Material use of DOPS	
	Dropped Object					Material used for one meter DOPS	m_tot	(L*A_beam+2*H_tot*A_column+2*A_beam)*ρ		1492,822587	kg
	Sludge disposal Tank										
Dropped object energy	E_dropped object	300	kJ	300000	J						
Amount of beams hit	n	2	-	2	-						
factor	γ	1,4	-	1,4	-						

	Type of Steel		Original Unit		Converted Unit				Formula		Unit
	S355									Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))		80769230769	N/m^2
E-modulus	E	210000	N/mm^2	2,1E+11	N/m^2						
Poissons ratio	v	0,3	-	0,3	-					Plastic Moment Capacity	
density	ρ	7850	kg/m^3	7850	kg/m^3	Plastic moment capacity	M_pl	f_y*α*W_y		685860	Nm
							M_pl			685,86	kNm
	Type of Beam										
	HEB 300									Impact Energy	
Shape Factor	α	1,15	-	1,15	-	Distribution Factor	β	(1/(n))*γ		0,7	-
Span	L	5,8	m	5,8	m	impact energy	E_impact	E_dropped object*β		210000	j=Nm
Height of beam	h	300	mm	0,3	m						
Width of beam	b	300	mm	0,3	m					Deformations	
thickness of body	t_b	11	mm	0,011	m	Effective length beam	L_eff	L-2*h		5,2	
thickness of flange	t_f	19	mm	0,019	m	angle of bending	θ	(E_impact)/(4*M_pl)		0,076546234	-
Area	A_beam	149,1	cm^2	0,01491	m^2	Sag middle beam	s	1/2*L_eff*θ		0,199020208	m
Moment of inertia y	I_y	25166	cm^4	0,00025166	m^4	curvature	κ	θ/h		0,255154113	m^-1
Section modulus y	W_y	1680	cm^3	0,00168	m^3	strain	ε	κ*1/2*h*100%		3,827311696	%
Moment of inertia z	I_z	8563	cm^4	0,00008563	m^4						
Section modulus Z	W_z	571	cm^3	0,000571	m^3					Generated force	
Torsion resistance	I_t	1850454,094	mm^3	1,85045E-06	m^3	Impact force	F	E_impact/s*1.5		1582753,846	N
Warping resistance	I_w	1,68779E+12	mm^6	1,68779E-06	m^6		F			1582,753846	kN
k coefficient flange	k_f	0,43	-	0,43	-						
k coefficient body	k_b	4	-	4	-					Buckling of column	
						Total height column	H_tot	H+s+0.2		4,399020208	m
	Type of column					Buckling capacity column	F_buck	(π^2*E*I_z) / (2*H_tot)^2		2811489,292	N
	RHS 300x300x6.3					Buckling capacity column	F_buck			2811,489292	kN
Column height	H	4	m	4	m						
Height of beam	h_column	300	mm	0,3	m					Plate Buckling of beam	
Width of beam	b_column	300	mm	0,3	m	Plate flange stress capacity	σ_cr_plate_f	(k_f*π^2*E) / (12*(1-v^2)*(b/t_f)^2)		327362968,2	N/m^2
thickness of body	t_b_column	6,3	mm	0,0063	m	Plate flange Force capacity	F_cr_plate_f	(σ_cr_plate_f*b*t_f) / 1000		1865,968919	kN
thickness of flange	t_f_column	0	mm	0	m						
Area of column	A_column	73,6	cm^2	0,00736	m^2					Lateral Torsion Buckling of beam	
Moment of inertia y	I_y_column	10500	cm^4	0,000105	m^4	Gravel lengte	L_g	L_g=L		5,8	m
Section modulus y	W_y_column	703	cm^3	0,000703	m^3	LTB moment capacity	M_cr	(π/L_g) * sqrt(E*I_z*G*I_t + ((π/L_g)^2)*E*I_z*E*I_w))		1156347,678	Nm
Moment of inertia z	I_z_column	10500	cm^4	0,000105	m^4					1156,347678	kNm
Section modulus Z	W_z_column	703	cm^3	0,000703	m^3						
										Material use of DOPS	
	Dropped Object					Material used for one meter DOPS	m_tot	(L*A_beam+2*H_tot*A_column+2*A_beam)*ρ		1421,254883	kg
	Sludge disposal Tank										
Dropped object energy	E_dropped object	300	kJ	300000	J						
Amount of beams hit	n	2	-	2	-						
factor	γ	1,4	-	1,4	-						

	Type of Steel		Original Unit		Converted Unit				Formula		Unit
	S355									Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))	80769230769	N/m^2	
E-modulus	E	210000	N/mm^2	2,1E+11	N/m^2						
Poissons ratio	v	0,3	-	0,3	-				Plastic Moment Capacity		
density	ρ	7850	kg/m^3	7850	kg/m^3	Plastic moment capacity	M_pl	f_y*α*W_y	563385	Nm	
							M_pl		563,385	kNm	
	Type of Beam										
	HEB 280								Impact Energy		
Shape Factor	α	1,15	-	1,15	-	Distribution Factor	β	(1/(n))*γ	0,7	-	
Span	L	5,8	m	5,8	m	impact energy	E_impact	E_dropped object*β	210000	j=Nm	
Height of beam	h	280	mm	0,28	m						
Width of beam	b	280	mm	0,28	m				Deformations		
thickness of body	t_b	10,5	mm	0,0105	m	Effective length beam	L_eff	L-2*h	5,24		
thickness of flange	t_f	18	mm	0,018	m	angle of bending	θ	(E_impact)/(4*M_pl)	0,09318672	-	
Area	A_beam	131,4	cm^2	0,01314	m^2	Sag middle beam	s	1/2*L_eff*θ	0,244149205	m	
Moment of inertia y	I_y	19270	cm^4	0,0001927	m^4	curvature	κ	θ/h	0,332809713	m^-1	
Section modulus y	W_y	1380	cm^3	0,00138	m^3	strain	ε	κ*1/2*h*100%	4,659335978	%	
Moment of inertia z	I_z	6595	cm^4	0,00006595	m^4						
Section modulus Z	W_z	471	cm^3	0,000471	m^3				Generated force		
Torsion resistance	I_t	1437164,839	mm^3	1,43716E-06	m^3	Impact force	F	E_impact/s*1.5	1290194,656	N	
Warping resistance	I_w	1,13015E+12	mm^6	1,13015E-06	m^6		F		1290,194656	kN	
k coefficient flange	k_f	0,43	-	0,43	-						
k coefficient body	k_b	4	-	4	-				Buckling of column		
						Total height column	H_tot	H+s+0.2	4,444149205	m	
	Type of column					Buckling capacity column	F_buck	(π^2*E*I_z) / (2*H_tot)^2	2754679,553	N	
	RHS 300x300x6.3					Buckling capacity column	F_buck		2754,679553	kN	
Column height	H	4	m	4	m						
Height of beam	h_column	300	mm	0,3	m				Plate Buckling of beam		
Width of beam	b_column	300	mm	0,3	m	Plate flange stress capacity	σ_cr_plate_f	(k_f*π^2*E) / (12*(1-v^2)*(b/t_f)^2)	337282497,3	N/m^2	
thickness of body	t_b_column	6,3	mm	0,0063	m	Plate flange Force capacity	F_cr_plate_f	(σ_cr_plate_f*b*t_f) / 1000	1699,903787	kN	
thickness of flange	t_f_column	0	mm	0	m						
Area of column	A_column	73,6	cm^2	0,00736	m^2				Lateral Torsion Buckling of beam		
Moment of inertia y	I_y_column	10500	cm^4	0,000105	m^4	Gravel lengte	L_g	L_g=L	5,8	m	
Section modulus y	W_y_column	703	cm^3	0,000703	m^3	LTB moment capacity	M_cr	(π/L_g) * sqrt(E*I_z*G*I_t + ((π/L_g)^2)*E*I_z*E*I_w))	868672,1771	Nm	
Moment of inertia z	I_z_column	10500	cm^4	0,000105	m^4				868,6721771	kNm	
Section modulus Z	W_z_column	703	cm^3	0,000703	m^3						
									Material use of DOPS		
	Dropped Object					Material used for one meter DOPS	m_tot	(L*A_beam+2*H_tot*A_column+2*A_beam)*ρ	1318,092529	kg	
	Sludge disposal Tank										
Dropped object energy	E_dropped object	300	kJ	300000	J						
Amount of beams hit	n	2	-	2	-						
factor	γ	1,4	-	1,4	-						

	Type of Steel		Original Unit		Converted Unit				Formula		Unit
	S355									Shear Modulus	
yield strength	f_y	355	N/mm^2	355000000	N/m^2	Shear modulus	G	E / (2(1+v))	80769230769	N/m^2	
E-modulus	E	210000	N/mm^2	2,1E+11	N/m^2						
Poissons ratio	v	0,3	-	0,3	-				Plastic Moment Capacity		
density	ρ	7850	kg/m^3	7850	kg/m^3	Plastic moment capacity	M_pl	f_y*α*W_y	469487,5	Nm	
							M_pl		469,4875	kNm	
	Type of Beam										
	HEB 260								Impact Energy		
Shape Factor	α	1,15	-	1,15	-	Distribution Factor	β	(1/(n))*γ	0,7	-	
Span	L	5,8	m	5,8	m	impact energy	E_impact	E_dropped object*β	210000	j=Nm	
Height of beam	h	260	mm	0,26	m						
Width of beam	b	260	mm	0,26	m				Deformations		
thickness of body	t_b	10	mm	0,01	m	Effective length beam	L_eff	L-2*h	5,28		
thickness of flange	t_f	17,5	mm	0,0175	m	angle of bending	θ	(E_impact)/(4*M_pl)	0,111824063	-	
Area	A_beam	118,4	cm^2	0,01184	m^2	Sag middle beam	s	1/2*L_eff*θ	0,295215528	m	
Moment of inertia y	I_y	14919	cm^4	0,00014919	m^4	curvature	κ	θ/h	0,430092552	m^-1	
Section modulus y	W_y	1150	cm^3	0,00115	m^3	strain	ε	κ*1/2*h*100%	5,591203174	%	
Moment of inertia z	I_z	5135	cm^4	0,00005135	m^4						
Section modulus Z	W_z	395	cm^3	0,000395	m^3				Generated force		
Torsion resistance	I_t	1237782,739	mm^3	1,23778E-06	m^3	Impact force	F	E_impact/s*1.5	1067017,045	N	
Warping resistance	I_w	7,53651E+11	mm^6	7,53651E-07	m^6		F		1067,017045	kN	
k coefficient flange	k_f	0,43	-	0,43	-						
k coefficient body	k_b	4	-	4	-				Buckling of column		
						Total height column	H_tot	H+s+0.2	4,495215528	m	
	Type of column					Buckling capacity column	F_buck	(π^2*E*I_z) / (2*H_tot)^2	2692447,907	N	
	RHS 300x300x6.3					Buckling capacity column	F_buck		2692,447907	kN	
Column height	H	4	m	4	m						
Height of beam	h_column	300	mm	0,3	m				Plate Buckling of beam		
Width of beam	b_column	300	mm	0,3	m	Plate flange stress capacity	σ_cr_plate_f	(k_f*π^2*E) / (12*(1-v^2)*(b/t_f)^2)	369738145,6	N/m^2	
thickness of body	t_b_column	6,3	mm	0,0063	m	Plate flange Force capacity	F_cr_plate_f	(σ_cr_plate_f*b*t_f) / 1000	1682,308563	kN	
thickness of flange	t_f_column	0	mm	0	m						
Area of column	A_column	73,6	cm^2	0,00736	m^2				Lateral Torsion Buckling of beam		
Moment of inertia y	I_y_column	10500	cm^4	0,000105	m^4	Gravel lengte	L_g	L_g=L	5,8	m	
Section modulus y	W_y_column	703	cm^3	0,000703	m^3	LTB moment capacity	M_cr	(π/L_g) * sqrt(E*I_z*G*I_t + ((π/L_g)^2)*E*I_z*E*I_w))	680588,8846	Nm	
Moment of inertia z	I_z_column	10500	cm^4	0,000105	m^4				680,5888846	kNm	
Section modulus Z	W_z_column	703	cm^3	0,000703	m^3						
									Material use of DOPS		
	Dropped Object					Material used for one meter DOPS	m_tot	(L*A_beam+2*H_tot*A_column+2*A_beam)*ρ	1244,394345	kg	
	Sludge disposal Tank										
Dropped object energy	E_dropped object	300	kJ	300000	J						
Amount of beams hit	n	2	-	2	-						
factor	γ	1,4	-	1,4	-						