

Limit-State Design of a Steel Storage Tank Foundation on a Crushed Rock Ring Based on Proven Soil Strength

K.J. REINDERS, B. SCHOENMAKER and W.A. NOHL

Geotechnical Department, Fugro GeoServices B.V., The Netherlands

Abstract. New vertical steel storage tanks founded on a shallow foundation of a crushed rock ring are planned at the same location of former storage tanks. The dimensions, loads and foundation of the new tanks are identical to the old tanks which were erected 40 years ago and demolished a few years ago. Despite the fact that the new tanks are identical to the old tanks, the stability calculation for the foundation of the new storage tanks did not fulfill the requirements of the present Eurocode 7-1. To ensure sufficient stability, additional measures like soil improvement are necessary. This is due to the fact that safety levels have much increased in the last 40 years. In order to optimize the design, it was decided to recalculate the stability using the code for existing structures "NEN 8707", which is currently being developed. According to NEN 8707 it is allowed to use a lower value for the reliability index β for existing structures compared to new structures, because of proven strength. Thus, lower partial load and material factors can be applied. These calculations with the adjusted partial factors resulted in a sufficient overall safety factor for the ultimate limit state for the hydro-test phase and the operational phase. Thus, using NEN8707, the tanks can be built on a crushed rock ring foundation without an expensive soil improvement.

Keywords. Stability, finite elements, existing structures, proven strength, crushed rock ring, β -factor, NEN8707

1. Introduction

Vertical cylindrical steel storage tanks are preferably founded on a shallow foundation with a crushed rock ring, mostly because of economic reasons. Even in locations with very soft soil, e.g. in the Western part of the Netherlands this type of foundation is used. However, when using this type of shallow foundation in areas with soft soils, the settlements and the stability of the foundation can be a problem. Thus, both mechanisms must be analysed carefully.

The settlements are usually checked with (EEMUA 2014). The stability of these tanks is calculated using Eurocode 7-1 (EN1997-1) with the Dutch National Annex.

In this paper a case is described where new tanks are located at the same position as the old tanks. Also, the loads and dimensions of the new tanks are identical to the loads and dimensions of the old tanks.

When analysing the stability using Eurocode 7-1 the tanks do not fulfill the present safety requirements. This is due to the

fact that safety levels have much increased after building the old tanks. To fulfill the present safety levels, additional measures, like soil improvement are necessary under the tank foundation.

In this situation the concept of proven strength was used. The concept of proven strength is based on the following: the construction has proven to be safe in the past, and therefore uncertainties have decreased, and lower safety margins are acceptable.

This concept is described in the NEN 8700 series. These codes are developed for the assessment of existing structures.

For the tanks a comparison is done between stability calculations according to Eurocode 7-1 and stability calculations according to NEN 8707.

2. Dutch code NEN8707

Geotechnical design of new structures in the Netherlands is performed according to the Eurocode 7-1 with Dutch national annex.

Furthermore a general code for existing structures is developed, known as NEN 8700. In this code methods are described how to check the safety of existing structures.

According to NEN 8700 it is allowed to use a lower value for the reliability index β for existing structures compared to new structures if the requirements of the NEN8700 are fulfilled. If all requirements are fulfilled, the reliability index can be adapted because of proven strength in the past. Thus lower load and material factors can be applied.

Based on NEN 8700, a code for the assessment of existing geotechnical structures, the NEN8707 is under development at the moment.

According to Rijneveld (2014) the code NEN8707 can be applied for stability issues when all following criteria are met:

1. The historical loads had been larger or equal to the future loads. Here all relevant load combination shall be considered;
2. In the historical situation no significant damage has occurred and the foundation of the construction performed as expected;
3. No significant, negative change has occurred in the geometry and/or the soil parameters;

If all these 3 criteria are met the following restrictions have to be applied to use the concept of proven strength:

- The design value of the maximum soil strength can only be as high as to withstand the maximum occurred load.
- Uncertainties between the historical and the future situation are supposed to be covered by the historical situation by assuming a high value of the soil strength and a low value of the load;
- Uncertainties in loads or strength that are not subject to change between the historical situation and the lifetime of the new structure need to be checked for all possible scenarios.

- The required information about the historical situation shall be reliable and verifiable.

3. Partial Factors with Eurocode 7-1 and NEN8707

In the Ultimate Limit State stability calculations the loads are multiplied with a load factor and the soil parameters are divided by a material factor (Design Approach 3 of Eurocode 7-1). The soil parameters for stability calculation are the effective internal friction angle, the effective cohesion and the undrained shear strength. These partial factors depend on the Consequence Class of the structure. According to Eurocode 7-1 most of the steel storage tanks are put in Consequence Class 2, indicating a risk of large economic impact, but minor risk of loss of life. The material and load factors have been determined based on the reliability index β .

In the second column of table 1 the reliability index and the partial factors are presented for Consequence Class 2, according to Eurocode 7-1. In the third column the adjusted partial factors according to NEN8707 are presented.

Table 1. Partial factors for Consequence Class 2 according to Eurocode 7-1 and NEN 8707

Parameter	Eurocode 7-1	NEN 8707
reliability index	$\beta = 3.8$	$\beta = 3.3$
Load factor n	1.20	1.1
liquid load		
$\tan \phi'$	1.45	1.3
c'	1.25	1.2
c_u	1.75	1.5

Using the proven strength concept from NEN8707, the material factors on $\tan \phi'$, cohesion c' and undrained shear strength c_u were reduced by approximately 10%, 4 % and 16% respectively. Furthermore, the load factor can be reduced by approximately 10 %.

4. Case of the storage tanks

Two vertical cylindrical storage tanks are planned on a foundation of a crushed rock ring. The tanks have a diameter of 14.5 m and a height of 16 m. They will contain benzene. Before going into operation, the tanks are filled with water (hydro test). The maximum load during the hydro test phase is 160 kPa and the maximum load in the operational phase is 140 kPa.

The new tanks are located on an existing plant where two old tanks with exactly the same dimensions and loads had been in use for the last 40 years. These tanks were demolished a few years ago.

NEN 8707 can be applied because all 3 criteria according to Rijneveld (2014) are met:

1. The new tanks are identical to the old tanks in diameter and loads
2. During their lifetime the settlements and the differential settlements of the old tanks were monitored. No damages or failure of the stability had ever occurred. The tanks performed as intended.
3. The soil conditions have not changed.

The soil conditions at the site consist of approximately 1.0 to 1.5 m sand, followed by a soft clay layer of 2 m thickness. Underneath this top clay layer a sand layer of 3 to 5 m thick is present. Below the sand, peat and silty clay layers are encountered to a depth of 20 m below surface level. From this level a dense sand layer is found.

5. Stability Analyses

Stability calculations for the hydro-test and the operational phase were performed using Finite Element software, Plaxis 2D.

First the historical load of the old tanks was simulated. Then calculations were performed for the hydro-test phase and the operational phase of the new tanks. The stability of the tanks in these phases were checked in the Ultimate Limit State. In appendix 1 all phases of the calculations are presented.

The calculations were performed using the partial factors from Consequence Class 2 of Eurocode 7-1 and using the proven strength concept of NEN 8707 with the adjusted factors. The applied parameter set for the stability calculations is presented in table 2.

Table 2. Parameters for calculation

Parameter	Characteristic value	Design values Eurocode 7-1	Design values NEN8707
Top Clay			
c' [kPa]	3	2.1	2.3
ϕ' [°]	20.0	16.0	16.7
Sand – Medium Dense			
c' [kPa]	0.0	0.0	0.0
ϕ' [°]	32.5	1.25	26.0
Crushed Rock			
c' [kPa]	5.0	3.5	4.2
ϕ' [°]	40.0	31.0	32.0
Load hydrofill phase	160 kPa	192 kPa	176 kPa
Load operational phase	140 kPa	168 kPa	154 kPa

The finite element calculations were performed using the following assumptions:

- Axial symmetric model;
- Hardening Soil material model (Brinkgreve et al., 2014);
- To determine the safety factor, the so called ϕ'/c' -reduction (Brinkgreve et al., 2014) was applied. A structure is safe when the overall safety factor resulting from the Ultimate Limite State calculations is greater than 1.0.
- Various loading phases were applied. In appendix 1 the calculation scheme is presented.

The input geometry is presented in figure 1.

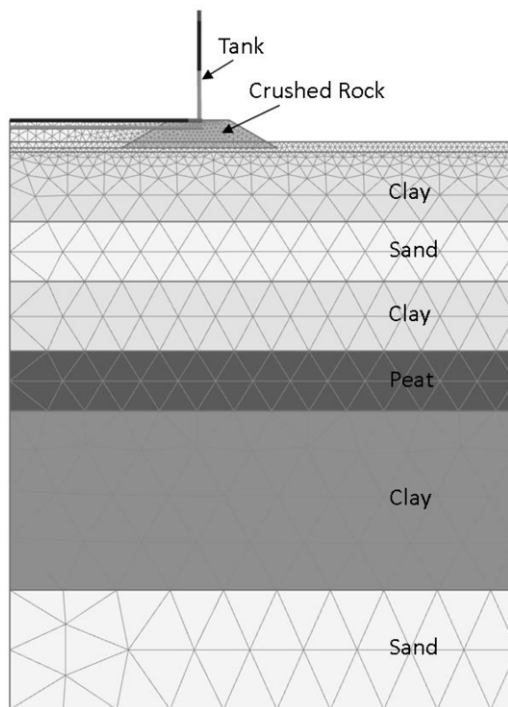


Figure 1. Geometry soil and tank.

6. Results

In table 3 the results of the stability calculation are presented for the calculation with the partial factors of the Eurocode 7-1 and with the adjusted partial factors according to NEN8707. The Safety Factor in the Ultimate Limit State calculation is given for the hydrofill phase and for the operational phase.

To fulfil the safety requirements in the Ultimate Limit State, the Safety Factor has to be equal or larger than 1.0. As shown in the table, the safety factor is smaller than 1.0 when performing the calculation with the partial factor from Eurocode 7-1. Based on these results, additional measures like soil improvement under the shallow foundation of the tanks is necessary. When performing the calculation with the partial factors based on NEN8707 the Safety Factor is 1.0 and the shallow foundation can be built without additional measures.

Table 3. Results of the Stability Calculations in Ultimate Limit State

	Safety Factor with Eurocode 7-1	Safety Factor with NEN8707
hydrofill phase	0.9	1.0
operational phase	0.9	1.0

7. Conclusion

For an economic design, in cases of existing structures the concept of proven strength can be taken into account. This concept is described in NEN8707.

In the case study of this paper this is illustrated by a tank foundation where 40 year old tanks were replaced by identical new tanks. In the last 40 years requirements for safety increased significantly. Therefore the new tanks could not have been built without significant soil improvement, when designed according to present regulations. However taking advantage of the proven strength of the soil and the foundation the safety margin can be reduced and replacement of the tanks was possible without any foundation improvement!

References

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Appendix 1, Calculation scheme ULS

In figure 2 the calculation scheme for the Finite Element analyses is presented. In the red box the phases of the history with the old tanks are modeled. The last phase in the red box represents the removing of the old tanks. The old tanks were build approximately 40 years ago and demolished a few years ago.

In the green box the phases of the construction of the new tanks is presented. First the tank shoulder (foundation) is modeled and then the whole tank.

In the small dark blue boxes, all the phases from hydrotest to operational phase for the new tanks are presented. First the tanks are filled with water (hydrotest). The duration of filling is 36 days. Then the tanks are emptied again and a consolidation phase is modeled to represent the time between end of the hydrotest and beginning of the operational phase.

Safety analyses have been performed after the hydrotest and after the operational phase. These analyses are presented in the orange box. The analyses have been done in the Ultimate Limit State.. In general when all phases are calculated using design values for load and strength parameters, the results will be conservative. Reference is made to the calculation scheme for sheet piles (CURNET, 2008).

Therefore, in the finite element analyses all phases except the final phase are analysed in Serviceable Limit State conditions, using characteristic values (no partial factors on loads and materials properties). Then the final phase is checked in the Ultimate Limit State and design values for the load and material are used.

This means that the partial factors were only applied to the loads and the material properties in the final phase.

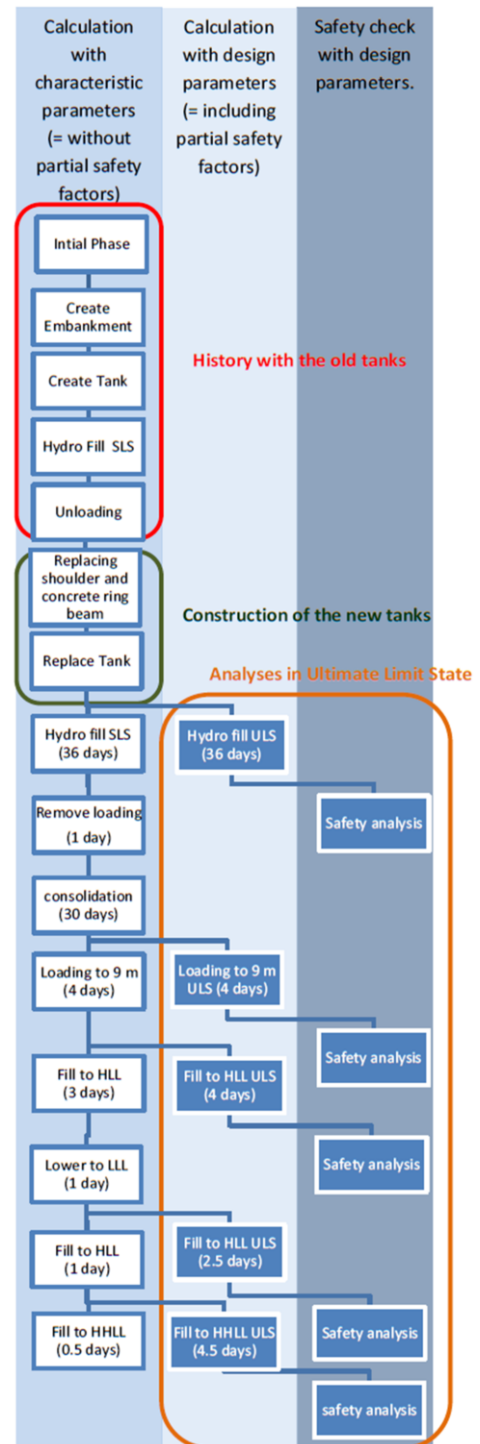


Figure 2. Calculation Scheme Finite Element Stability Analyses.