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A Whole Lot of Shaking — Seismic Load Considerations in Thickener Design

E. Hooimeyer *Outotec Pty Ltd, Australia*

J. Rosart *Outotec Pty Ltd, Australia*

Abstract

In paste and thickened tailings disposal, one of the most structurally significant components is the thickener. When calculating the strength of the supporting structure, the effects of seismic activity become an important design consideration, particularly in countries prone to high activity. Thickener tanks can hold in excess of 10 million litres of slurry, having masses greater than 15,000 tonnes. Thus, even in relatively low seismic zones, a thorough understanding of the seismic behaviour of these tanks is critical when it comes to structural integrity and safety. A further consideration is the financial and operability benefits when examining structure weight and footing design.

The influence of ground conditions on the magnitude of forces is often overlooked. It is commonly known that more earthquake damage occurs in softer soils than rock. This paper will explore different ground conditions and show how site-specific ground data can be used to make informed decisions on thickener selection.

Another significant consideration is thickener shape. A parallel here is building design for earthquake sensitive regions. Natural frequencies are evaluated to see if structures are prone to damage, showing the critical geometry one should avoid. In thickeners, sizing and shape is driven by process decisions. There are, however, alternative shapes that can perform equally well. This paper will explore thickener shapes and the suitability for various seismic conditions. It will also explore support methods and their response to seismic loads.

1 Introduction

Safety and structural soundness are key prerequisites when designing thickeners. A typical 20 m diameter thickener could easily be 20 m tall, which is equivalent to a seven storey high-rise building, and contain three olympic-sized swimming pools of slurry. Such a building would never be designed or built without a comprehensive understanding of ground conditions. Ground conditions have a great influence on the seismic response of a structure.

The total cost of a thickener is not dependent on steel alone. The resultant civil and operating costs need to be evaluated when financing a complete thickener. Civils can represent 20 to 30% of total costs and could easily increase if not correctly considered when designing thickener tankage. In an ideal world, the engineering departments of thickener suppliers would enjoy excellent communication and flow of information between all engineering disciplines involved in a thickener project; particularly between civil and steel design.

The benefits of designing and building structurally sound thickeners are made clear when an earthquake occurs. In 2007 an earthquake measuring 7.8 on the Richter scale occurred in South America, causing loss of human life and irreparable damage. Four Outotec thickeners, including an 18 m high compression thickener, were close to the epicentre of the earthquake. The only reported damage to the thickeners was the short circuiting of a powerpack electric motor that was caused from waves splashing over the bridge.

The design of thickeners goes through many stages and involves multiple disciplines of engineering. Firstly, the basic technology is selected by process engineers who need to understand the intent of the thickener and the desired outcomes. Geomechanical engineers then get involved in defining the disposal method. Underflow transport options are examined by the pump and pipeline design engineers.

From these outcomes, the type of tailings thickener is defined, be it high rate, high compression or paste. From then on, thickener design engineers become part of the decision making process.

The thickener engineer defines the strength requirements of the thickener to correctly process and contain the expected contents. Thickener tanks can hold in excess of 10 million litres of slurry, having masses greater than 15,000 t. The engineer needs to work closely with the civil engineer, as the forces to be restrained at ground level can be substantial. Good communication between the thickener engineer and the civil engineer can save significant costs as simple assumptions and their impact become understood by both parties.

This paper explores how simple decisions regarding geometry and thickener support can impact the civil design. Other factors such as ground conditions and thickener shape also play key roles in thickener selection. Looking at seismic effects, the paper will discuss how understanding local conditions will give the best outcome.

2 Ground conditions

In general, seismic damage is greater in regions with softer soils when compared to rock. This greater damage is observed in both rigid and flexible structures. Figure 1 compares typical response spectrums for rock and stiff soil extracted from the International Building Code (IBC, 2006). It shows greater ground accelerations are experienced in softer soils for structures of equivalent natural period.

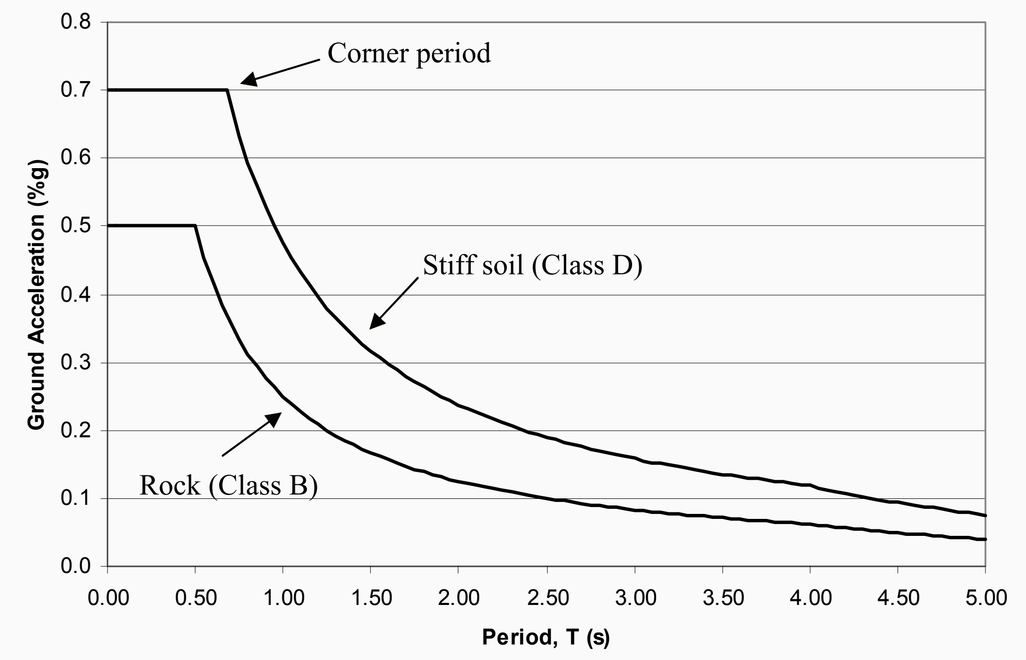

Figure 1 Typical response spectrums in IBC (2006) for rock and stiff soil sites

2.1 Site class definitions

There are six site classes listed in IBC (2006). The same basic classification system is found in other international seismic codes. The best to worst, in terms of limiting the ground motions on a structure, are:

1. Hard rock.
2. Rock.
3. Very dense soil and soft rock.
4. Stiff soil.
5. Soft soil.
6. Cohesionless soil (i.e. sand).

International seismic codes typically require a geotechnical investigation of the top 30 metres of rock and soil to classify the ground conditions present at a site; otherwise a default soil profile must be assumed. IBC (2006), ASCE 7 and API 650 (2003) specify a site profile D (stiff soil) be used for any unclassified site, which will give conservative results.

Although many mine sites have soft or stiff soil on the surface, this doesn't necessarily make them soil sites. Rock classes A and B can have up to three metres of any type of soil between the underside of the footings and the underlying rock. Consequently, for thickener footings one metre or deeper, the underlying rock can be four metres below grade.

Outotec supplies thickener technology to clients around the globe and experience has shown that ground conditions are rarely specified. Peak ground acceleration is almost always given since this can be obtained from maps in the local seismic code. But this is not the case for ground conditions since they are very site specific. As a result, thickener suppliers must take a conservative approach with regard to seismic design and the provision of footing loads when ground conditions are unknown.

2.2 Site classification methods

There are three standard parameters that can be measured to determine a site classification. These are the average shear wave velocity, penetration resistance, and soil shear strength in the top 30 m. Shear wave velocity is the code-preferred parameter and is the only one allowed for the hard rock and rock classifications. Of the shear wave methods, cross-hole seismic testing in accordance with ASTM D-4428 (see Figure 2) is the most accurate. It involves two to three vertical borings 30 m deep. A shear wave source and a geophone are lowered into separate borings and readings are taken at various depths. Unfortunately, this method is expensive and as presented by Fouse (2004), can cost anywhere from US$ 10,000 to US$ 30,000. A less expensive option, using surface seismic refraction measurement in accordance with ASTM D-5777 is generally preferred, since no borings are required and cost is in the order of US$ 5,000. This is a small investment for a multi-million dollar project.

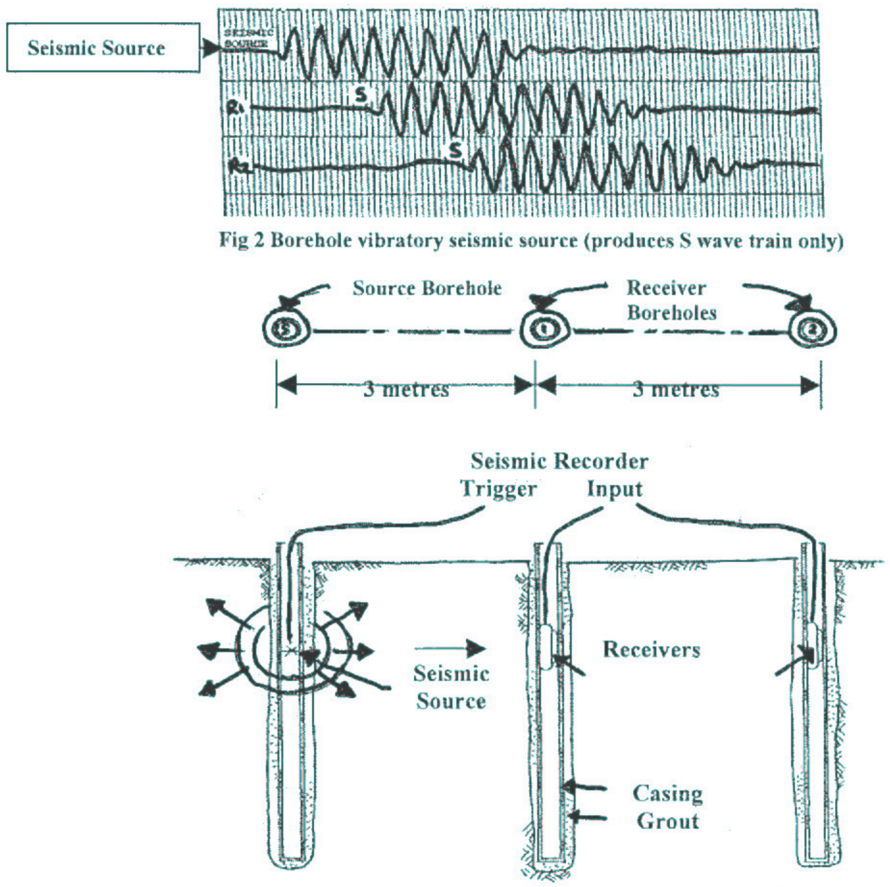

Figure 2 Cross-hole seismic testing procedure from ASTM D-4428

Ideally, any reasonably sized thickener project should have an accurate site classification carried out prior to detailed design commencing. For large and tall elevated thickeners, the effect of ground conditions becomes critical to safety and economical design, especially in areas of high seismic activity.

2.3 Response spectrum profile

The idealised response spectrum in Figure 1 shows a maximum value for small natural periods as a straight line. The change in slope point is called the corner period and it can be significantly shorter for rock conditions. In this IBC (2006) example, 0.5 and 0.7 seconds are the corner periods for rock and stiff soil respectively. In different regions or countries, this corner period can be as low as 0.3 seconds for rock and greater than 1 second in soft soil. Large elevated paste thickener tanks can have natural periods in the range of 0.5 to 1 second and will experience lower seismic loads in favourable ground conditions. There are also several ways of making the structure more flexible (thereby increasing the natural period) to reduce loads even further, although there are practical limits. For a large paste thickener with a natural period of 0.7 seconds and a rock site class, a 25% decrease in seismic loads is achieved compared to a more rigid structure. In a stiff soil site class, no such load reduction is achieved. Without knowledge of ground conditions exploring the potential for load reduction is not possible.

2.4 Further considerations

A lesser known feature of ground conditions is their dependence on the level of seismicity in a region. It was observed that weak sub-surface rock motion is amplified to a much larger extent by overlying soft soil deposits than in strong sub-surface rock motion. In areas of high seismicity, short-period sub-surface rock motion may even be dampened by overlying soils when they are very soft (IBC (2006) site class E). Using the Uniform Building Code (UBC, 1997) convention, it was found that in lower seismic regions (zones 1 and 2), poor ground conditions can amplify seismic loads for rigid structures by 70 to 150%, whereas in high seismic regions (zones 3 and 4) the amplification is only 10 to 20%. This relationship is shown in Figure 3 below. However, it should be noted that corner periods remain largely unchanged by the level of seismicity; hence even in high seismic regions very significant load reductions will be experienced by flexible structures in favourable ground conditions.

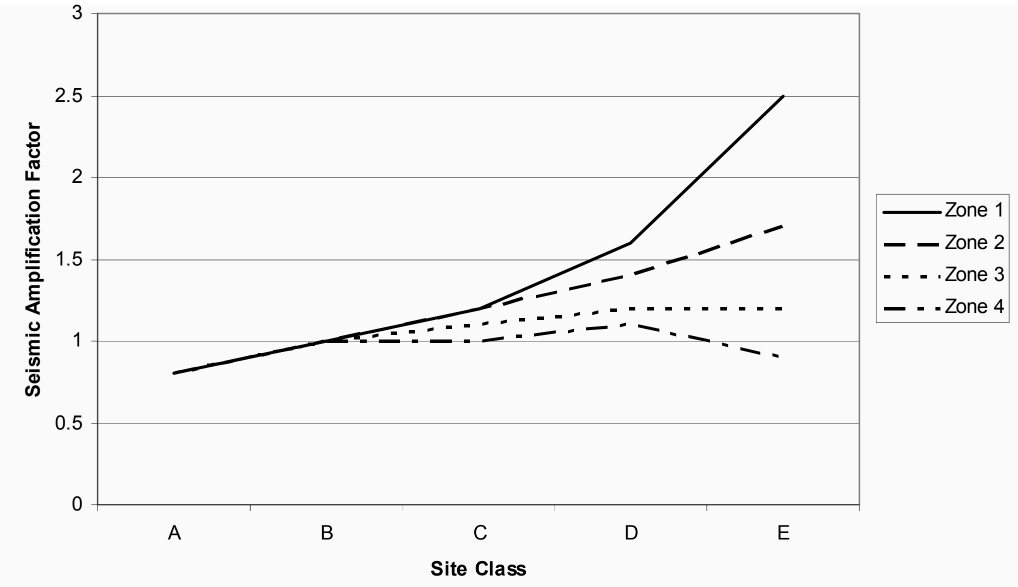

Figure 3 Seismic amplification factor versus site class for rigid structures

From a practical standpoint, this means that knowing the true ground conditions can be beneficial for any level of seismicity. For thickeners in UBC zones 1 or 2, conservative ground condition estimates can produce seismic loads similar to zone 3. For high seismic regions, a conservative ground condition makes high loads even higher, and disallows the use of flexible structure design. In summary, a detailed ground condition investigation can ultimately lead to a more economical thickener design from lower seismic loads.

3 Ground clearance

One of the key influences on structural stiffness is column height. In one particular case study, Outotec was to supply six-off 23 m diameter high rate CCD thickeners. These six thickeners were to be installed in a relatively high seismic region with a seismic acceleration factor of 0.3 (API 650, 2003). The last sizeable land-based earthquake in the area had a magnitude of 7.5 and killed 23,000 people.

The CCD thickeners were to operate in series, with gravity overflow from one thickener to the next. Only underflow was to be pumped. To allow gravity flow of the liquor, a 1.2 m height differential between adjacent thickeners was required. The height change was effected using different leg heights for each alternate pair of thickeners. Each thickener would have a single central support plus two rings of 12 legs supporting the elevated tank. The completed thickeners are shown in Figure 4.

Figure 4 Six 23 m diameter high rate CCD thickeners

When calculating the seismic forces, the change in ground clearance needed to be considered. The response of a structure to ground motion is greatly influenced by the stiffness of the structure. A way of describing this is the natural period, which takes into account the potential of a structure to resonate with a pulsing movement. Changes in ground clearance influence the period of a structure similarly to how the tension in a guitar string affects the sound that emanates. We can also influence the period through support stiffness, as we affect the pitch through guitar string thickness.

A comparison of the natural periods of the thickeners was carried out to see if there was a trend in stiffness and hence seismic sensitivity as ground clearances were changed. Only the alternate pairs of thickeners were checked as ground clearance was obtained through columns and footings, with a major step height at every second tank. Columns were sized to support the total slurry load without buckling for the various lengths. Total structural stiffness was calculated for sideways forces to calculate the period, which is also significantly affected by the supported mass. Table 1 gives the resultant natural periods under normal operating conditions for supports with and without radial bracing.

Table 1 Natural period of CCD thickeners

Tank	Ground Clearance	Without Radial Bracing	With Radial Bracing
CCD 1 and 2	2700 mm	0.33 s	0.34 s
CCD 3 and 4	3900 mm	0.37 s	0.37 s
CCD 5 and 6	5100 mm	0.39 s	0.42 s

As expected, the tankage has increased period as leg height increases. There are minor changes in period between bracing types. This can be attributed to bracing angle and influence of the central support member.

Regardless of support type, the strength requirements to resist lateral loads will influence the natural period of a structure. With careful layout, the addition of radial bracing can have minimal impact on accessibility under the thickener. For this high seismic case radial bracing was used.

Having determined the stiffness characteristics of the thickener supports, the restraining forces to resist an earthquake were calculated. Table 2 compares the sideways forces for each design relative to the shortest leg height tank. Of interest is the transfer of load away from the centre post to the inner and outer legs for the taller thickeners.

Table 2 Relative column base shear of CCD thickeners

Tank	Central Support	Inner Legs	Outer Legs	Total Sideways
CCD 1 and 2	100%	100%	100%	100%
CCD 3 and 4	72%	106%	99%	100%
CCD 5 and 6	50%	111%	102%	100%

When reviewing the vertical resultant load, there is a significant impact due to ground clearance. Simply put, the contents' centre of mass is lifted as the clearance increases. This makes for a bigger moment from the same force, which results in larger vertical up and down forces in the outer columns. There is no vertical force in the central support due to sideways force. Table 3 shows a comparison of overturning moment and resultant maximum vertical loads in the outer columns relative to the shortest leg height tank.

Table 3 Relative column vertical load of CCD thickeners

Tank	Overturning Moment	Outer Leg Vertical Load
CCD 1 and 2	100%	100%
CCD 3 and 4	123%	125%
CCD 5 and 6	146%	150%

We see here a linear relationship between load height change and vertical load in the outer columns and a redistribution of horizontal forces even though the total load did not change. This shows that an increase in ground clearance will increase forces to be restrained by the footings which will result in added costs.

4 Floor slope

Different styles of thickeners have traditionally been supplied with fairly common floor slopes. This typically ranges from 1:6 floor slopes for high rate thickeners through to 45° for some paste thickeners and even 60° for some thickener types. This section of the paper will explore different floor slopes and the impact on footing loads due to slurry and earthquake loads.

To accurately compare the results, certain geometric constants were defined. Tank diameter was to be 20 m for all thickeners and sidewall height 10 m. The SG of slurry was constant with a bed being formed 5 m from the top of the liquid and seismic acceleration constant across thickeners. Three rings of support columns and constant ground clearance at the central support were used for all thickeners. Radial and circumferential bracing was included in the design. Floor slope was 1:6 (HRT), 1:3 (HCT), 30°, 40° and 45° (paste). These configurations are shown schematically in Figure 5 and tabulated in Table 4.

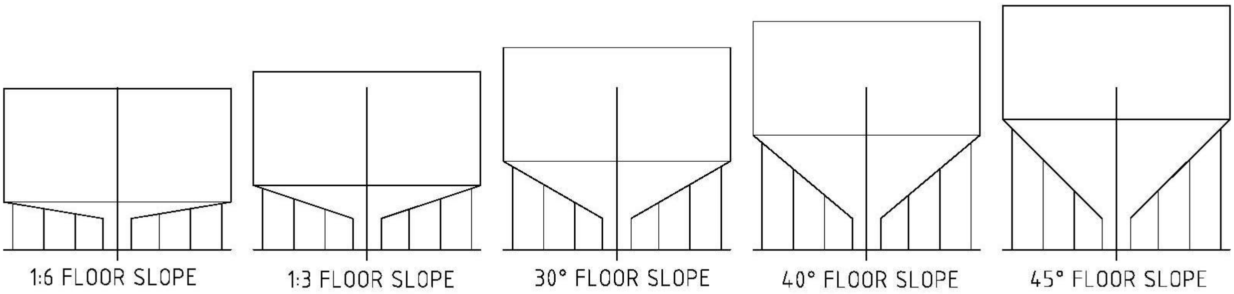

Figure 5 **Outline diagrams of tanks under review**

Table 4 **Basic geometric comparison of thickeners**

	1:6	1:3	30°	40°	45°
Total tank height (m)	14.2	15.58	17.59	19.82	21.25
Maximum mud height (m)	9.2	10.58	12.59	14.82	16.25
Ground clearance at wall (m)	4.2	5.58	7.59	9.82	11.25
Total volume (m^3)	3316	3491	3746	4020	4189
Seismic load height (m)	7.26	8.26	9.7	11.32	12.36

From this we can see there is a more significant change in total tank height than volume when you increase floor slope. This results in larger compression load on the slurry, which may help to obtain slightly increased underflow density. It also results in the need to consider access to the bridge as the thickener approaches a multi-floor building height.

We then compare the distribution of loads through the columns to the footings. The table below gives a distribution of footing loads as a percentage of total applied loads for each ring of legs.

Table 5 **Column vertical load due to slurry contents as percentage of total load**

	1:6	1:3	30°	40°	45°
Central support	21%	29%	31%	30%	32%
Inner ring	26%	23%	21%	19%	18%
Middle ring	31%	25%	23%	23%	22%
Outer ring	22%	22%	25%	28%	28%

We see that as floor slope increases there is an increased proportion of load to the central support and outer supports. The most balanced designs are the 1:6 HRT and 1:3 HCT cases.

Having completed the strength checks for vertical load and sized the support structure, we can check natural periods to see the effect of floor slope. Table 6 gives natural periods for each tank. These periods correlate well with the paste thickener natural periods assumed in the ground conditions section of this paper.

Table 6 **Natural periods for thickeners**

	1:6	1:3	30°	40°	45°
Natural period (s)	0.33	0.41	0.48	0.58	0.64

Even though the conical shape of the floor increases in stiffness as the slope increases, the overall natural period also increases which indicates a reduction in stiffness of the complete structure, resulting in a stiff centre and flexible supports with steep cone thickeners.

A similar review was carried out for base shear due to earthquake to see how the load distribution varies based on floor slope. An acceleration coefficient of 0.2 g and soil site class D were used. There was no natural period reduction in seismic load since the most flexible thickener had a natural period less than the corner period. Table 7 compares the shear per ring of columns.

Table 7 Seismic base shear distribution per ring of column

	1:6	**1:3**	**30°**	**40°**	**45°**
Central support	38%	48%	76%	73%	76%
Inner ring	13%	11%	4%	2%	2%
Middle ring	15%	12%	5%	3%	2%
Outer ring	34%	28%	15%	22%	20%
Total shear (kN)	4923	5350	5773	6646	7053

Even though there is only a 26% increase in tank volume across the tanks the resultant total base shear increases by 43% when comparing the shallow and steepest floors. This is due to all the additional mass acting in unison with the structure and not dynamically. We also see a significant shift of base shear away from the outer columns to the centre post as the floor slope increases. This regularly causes the civil engineer problems when designing footings as the available bearing area for the footing is reduced.

The final check is to compare column axial load due to the overturning moment.

Table 8 Seismic overturning moment distribution per ring of column

	1:6	**1:3**	**30°**	**40°**	**45°**
Central support	7%	8%	12%	14%	16%
Inner ring	6%	6%	4%	3%	2%
Middle ring	2%	2%	2%	3%	3%
Outer ring	85%	83%	81%	80%	79%
Total moment (kNm)	66,649	74,072	88,132	102,960	111,308

As expected, the overturning moment significantly increases as floor slope increases. This is due to the mass centre rising as the ground clearance increases. We also see a transfer of moment towards the centre post as floor slope increases, but not as significantly as base shear. As slope increases we see more conical stiffness effects influencing the load distribution. This can work against the civil designer who needs to design the foundation to resist this overturning moment over a small area.

5 Case study – 40 m free-standing paste thickener

Thickeners in high seismic regions can have base shears ranging anywhere from 15 to 30% of the slurry weight. Steel bracing is used to transmit these forces into the foundation. Paste thickeners are no different, however due to the extremely heavy slurry loads present in large diameter tanks, bracing weight becomes significant and foundation loads are severe.

A 40 m free-standing paste thickener with a 10 m sidewall, 30° floor slope, and 3 m high centre support is shown in Figure 6.

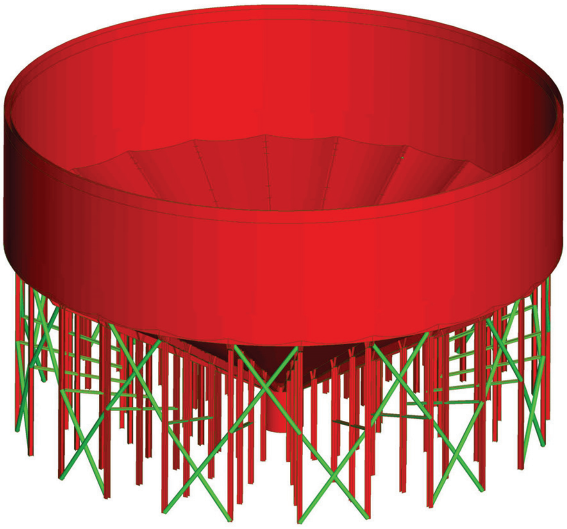

Figure 6 40 metre free-standing paste thickener

Possible designs for two different ground conditions will be evaluated.

5.1 Favourable ground conditions (rock)

Typical free-standing high rate thickeners have a low profile and are fairly rigid structures. But since paste thickeners have higher sidewalls and steep floor slopes, they are more flexible due to their higher mass centre. As seen from the section on ground conditions, this can be advantageous for limiting seismic reactions.

For initial design checks, a rigid structure can be assumed (natural period of 0.2 seconds). For this Paste thickener, base shear equals 56,565 kN in site class B for a UBC zone 4 region.

Evaluating the true natural period of the structure, it is found to be 0.71 seconds. Since the corner period for site class B in this example is 0.5 seconds, a significant reduction in seismic load is achieved. The result is 39,684 kN, which is a 30% reduction. This becomes an iterative process, since reduced load allows lighter bracing, which makes the structure more flexible. The final result is a base shear 35% lower than the rigid structure case.

Counter-intuitively, the deflection of the structure actually decreases under the design earthquake when it is more flexible. So, adverse structural loads (P-delta effects) due to movement of the tank are actually more of a concern for the rigid case.

5.2 Unfavourable ground conditions (soft soil)

In soft soil the corner period can be one second or more. Most thickener structures will not achieve a natural period anywhere near this high. Therefore, making the structure more flexible doesn’t achieve any load reduction. The seismic loads are very high in this scenario and tend to concentrate most of the shear on a few individual footings depending on the direction of the earthquake, which makes all of the footings very heavy.

In-ground tanks can be advantageous in high seismic regions since the base shear is spread over a large area, rather than in a few individual columns. However, pumping paste to the surface is problematic, which is where elevated tanks have significant process advantages over in-ground designs. A suitable compromise is a half-buried option as shown in Figure 7.

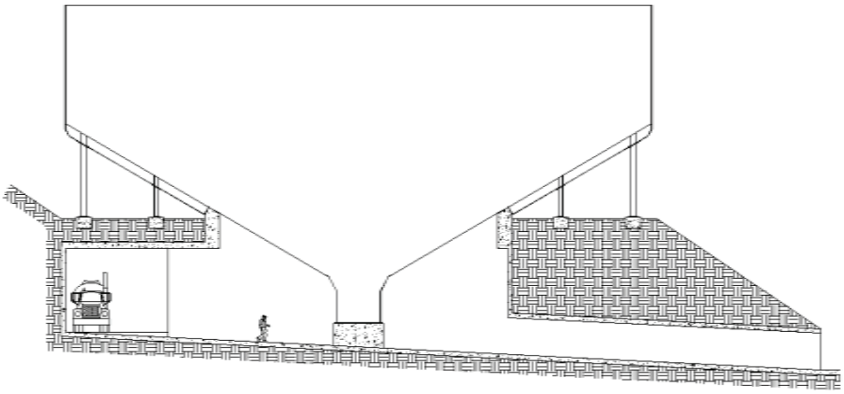

Figure 7 40 metre half-buried paste thickener

The design of the tank is very similar to the free-standing option, except that the outer columns have been shortened and the inner column replaced by a ring beam that is bolted to the foundation. The seismic base shear is then split 30% to the outer columns and 70% to the ring beam for this example. The underflow of the thickener is still below grade, but isn't nearly as deep as a fully in-ground tank.

6 Summary

With an improved understanding of ground conditions, both thickener and civil design can be optimised, whilst still ensuring the key prerequisites of safety and structural integrity are achieved. For a relatively small cost, large financial benefit can also be realised. The message needs to be reinforced in the industry that ground conditions are not to be evaluated at the surface but on conditions 4 m to 30 m below ground.

A reduced ground clearance will reduce the vertical loads on the outer columns. This will save on civil costs but, as in the example given in Section 3, may result in extra equipment costs. There is no stock-standard solution, as for each individual application there will be an ideal height.

As floor slope increases, there is a redistribution of loads that can significantly increase civil costs. Flatter floors give more even distribution and smaller vertical loads at the expense of total slurry height.

When on rock, it will often be very favourable to install elevated thickeners even beyond current perceived size limits. The cost saving can be enormous for the civil contractor as he does not need to cut out rock. For other soil types this is not as clear and alternatives can be considered.

There is no off-the-shelf answer to designing such large equipment for all seismic conditions. Good communication between parties will benefit all in developing the most ideal result.

References

API 650 (2003) 10th Edition, Addendum 3. Welded steel tanks for oil storage. American Petroleum Institute, Washington, D.C., USA.

Fouse, J. (2004) Geotechnical aspects of the IBC 2003 seismic design. ASCE/EERI Seminar on the IBC 2003 Code, St. Louis, USA, viewed 3 October 2008, http://sections.asce.org/stlouis/SEI/IBC_PPT/10-14-04_IBC_Seminar_Section_1615_Fouse.pdf

International Building Code (IBC) (2006) International Code Council, Country Club Hills, Illinois, USA.

Uniform Building Code (UBC) (1997) Volume 2: Structural Engineering Design Provisions. International Conference of Building Officials, Whittier, California, USA.