Technical Note 15 – Manhole Flotation

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1 Objectives

- Investigate factors which affect manhole floatation
- Determine if differential displacement of manholes observed after the Canterbury Earthquake Sequence (CES) is likely to be due to manhole floatation or ground settlement.
- Identify methods of reducing likelihood of floatation

2 Introduction

In the aftermath of the CES, numerous manholes were found to be protruding from the surrounding ground. This differential displacement may be caused by floatation of a manhole or settlement of the surrounding ground. It was not immediately clear which cause was responsible for the observed differential displacement. This note discusses whether the displacement is likely due to manhole floatation or ground settlement.

Floatation refers to the upward movement of the manhole relative to the surrounding ground as a result of buoyancy forces imposed on it. Floatation may be referred to as buoyant uplift however the term "floatation" is used throughout this document for consistency.

Floatation can cause damage to adjacent infrastructure and connections. The protrusion can also be a hazard to the public due to risk of collision. Repair of floated manholes typically requires extensive excavation, costly construction techniques or full replacement. As such, preventing floatation is key component of reducing the damage caused by earthquakes.

Floatation occurs when the total upwards force acting on a manhole is greater than the total downwards/resisting force acting on the manhole. This relationship is represented by the Factor of Safety (FOS) against floatation as shown in Equation 1. Floatation is possible when the FOS falls below 1.

$$FOS = (F_T + F_{WS} + F_{SP})/ (F_B + F_{EPP})$$ [1] (1)

The upwards force component of the FOS comprises static uplift force (F_B) and elevated buoyant force caused by excess pore pressure (F_{EPP}). The resisting force component of the FOS comprises the weight of the structure (F_T), soil weight (F_{WS}) and the shear strength of the overlying soil (F_{SP}) (D. A. Rowland, 2015).

Liquefaction resulting from an earthquake has the potential to increase the likelihood of floatation. Liquefaction refers to the phenomena where saturated loose sandy soils behaves as a liquid when cyclic loading associated with earthquake causes pore water pressure in the soils to increase. The increased pore water pressure can cause soil particles to separate thereby significantly decreasing shear strength (i.e. a decrease in F_{SP}). Increased pore pressure also increases buoyant forces on the manhole (i.e. an increase in F_{EPP}). The decreased soil shear strength and the increased buoyancy can cause floatation.

[1] (D. A. Rowland, 2015)

3 Investigation and Analysis

A model was developed to analyse major factors that affect floatation of a manhole. The model was a spreadsheet that incorporates manhole dimensions, geotechnical parameters and Equation 1. The manhole arrangement specified in NZS 4404:2010 (Standards New Zealand, 2010), shown in Figure 3-1, was used as the basis for the model. Less commonly used or outdated arrangements such as cast in-situ or square manholes were not analysed. The key output from the model is the FOS.

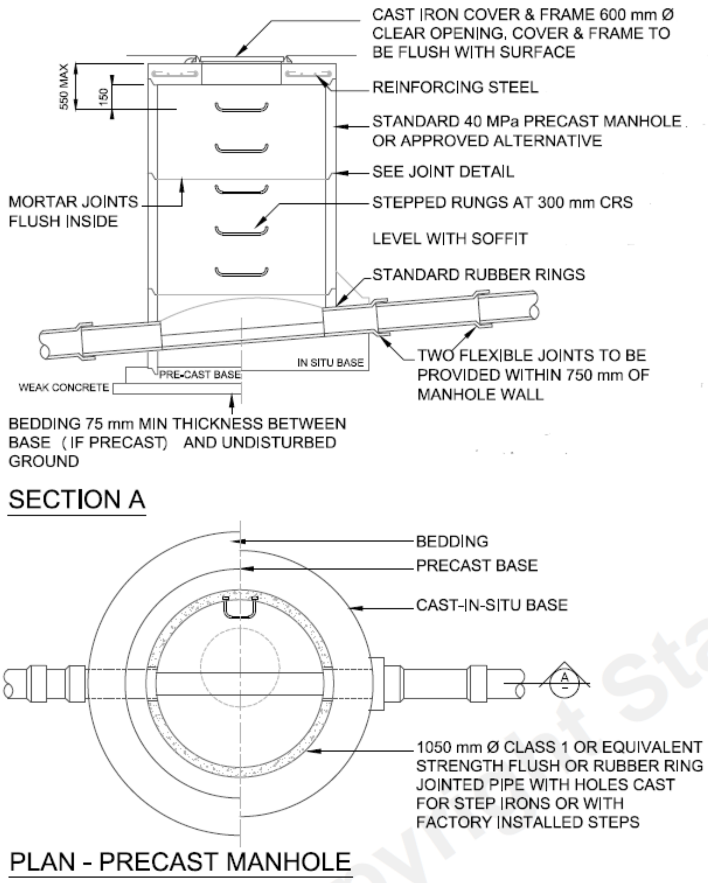


Figure 3-1 Manholes Standard Detail (Extract from NZS 4404:2010 (unnecessary text removed)

The parameters of the model are discussed below:

Size	Manhole dimensions provided by manufacturers Hynds and Humes are used. These dimensions along with an assumed concrete density of 24 kN/m^3 allow the calculation of the weight of the manhole. 1050 mm, 1500 mm and 2050 mm nominal internal diameter manholes were tested (described hereafter as 1m, 1.5m and 2.0m diameter). The dimensions used are compliant with the specifications of NZS 4404:2010 and represent actual manhole sizes available from suppliers.
Depth	Manhole depths up to 10 m were tested
Flanged vs Unflanged Base	The base of manholes can be fitted with a 150 mm flange which extends beyond the external wall of the manhole. This parameter captures the availability of the flange. The model allowed the effect of different sized flanges to be considered.
Soil shear strength (Su)	Soil shear strength is assumed to be 20 kN/m^2 under normal conditions.
Liquefied shear strength (Su liq)	Liquefied shear strengths of 0 to 5 kN/m^2 were analysed. Refer to the Discussion section for further information on liquefied shear strength.

The following assumptions were made in developing the model and represent a conservative approach to establishing FoS:

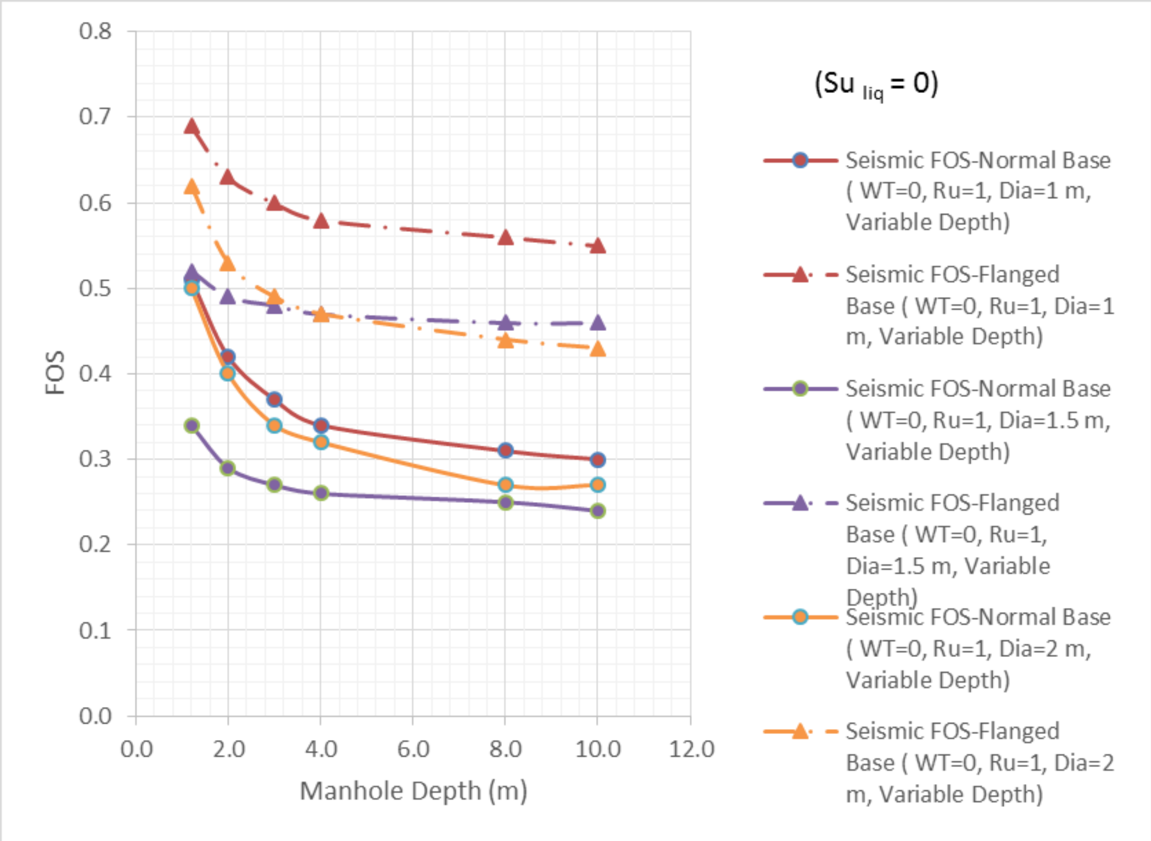
- The water table is at ground level meaning the soil is saturated. This condition represents liquefaction of the soil for the full depth of the manhole
- Complete liquefaction of the soil. Complete liquefaction of soil results in the greatest loss in shear strength. If the soil liquefies partially, it would result in lesser reduction in shear strength
- No overlying material. Typically, a manhole will have some overlying material in the form of backfill or pavement material above the manhole lid and around the cover and frame. The overlying material contributes to the resisting force acting on the manhole
- No benching. Benching refers to the forming of channels inside the manhole using concrete. A manhole will typically contain some form of benching in its internal base. However, the weight of benching is comparatively small and comprises 3-5 percent of the total resisting force of the manhole therefore is excluded from the model.
- No connecting pipework. The role of connecting pipework in promoting or restraining flotation is unclear. Connecting pipework may help restrain manholes in some conditions, although Scally (2013) reports cases of pipelines that floated between manholes when the manholes did not float.

4 Results and Discussion

The charts below (**Error! Reference source not found.**) shows the output from the analysis. The change in FOS with manhole depth, diameter and the effect of a flanged base (150 mm projection) is shown for varying liquefied shear strengths. FOS in non-liquefied conditions is far in excess of 1 and poses no threat of floatation therefore no charts are provided.

The comparative plots showing variation of FOS for different manhole depths (1 m, 2 m, 3 m, 4 m, 8 m and 10 m), and different manhole diameters (1 m, 1.5 m and 2 m) are shown below.

In general, it was observed that for the all the diameters analysed, the FOS decreases as the depth of manhole increases. The rate of decrease in FOS is generally higher up to the manhole depth of 4 m. However, there was no significant change in FOS between the manhole depths 4 m and 10 m. Similar trends were observed for the various liquefied shear strength (0 to 5 kPa) of soils. It is further to be noted that the FOS for small diameter (1 m diameter) manholes is higher than that of large diameter (2 m) manholes for similar conditions (i.e. depth, soil strength.



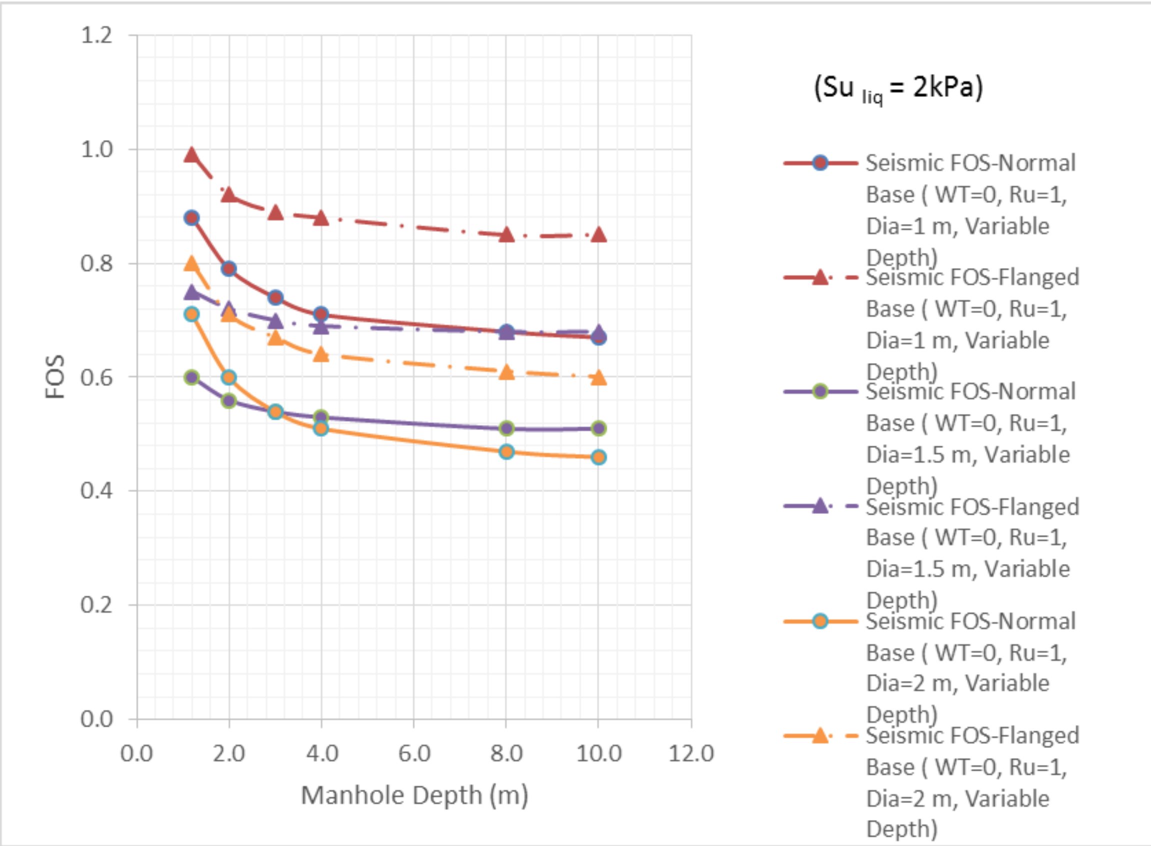


Figure 4-1: Variation of FOS with Respect to Depth at 1m diameter (top) and 1.5 m diameter (bottom)

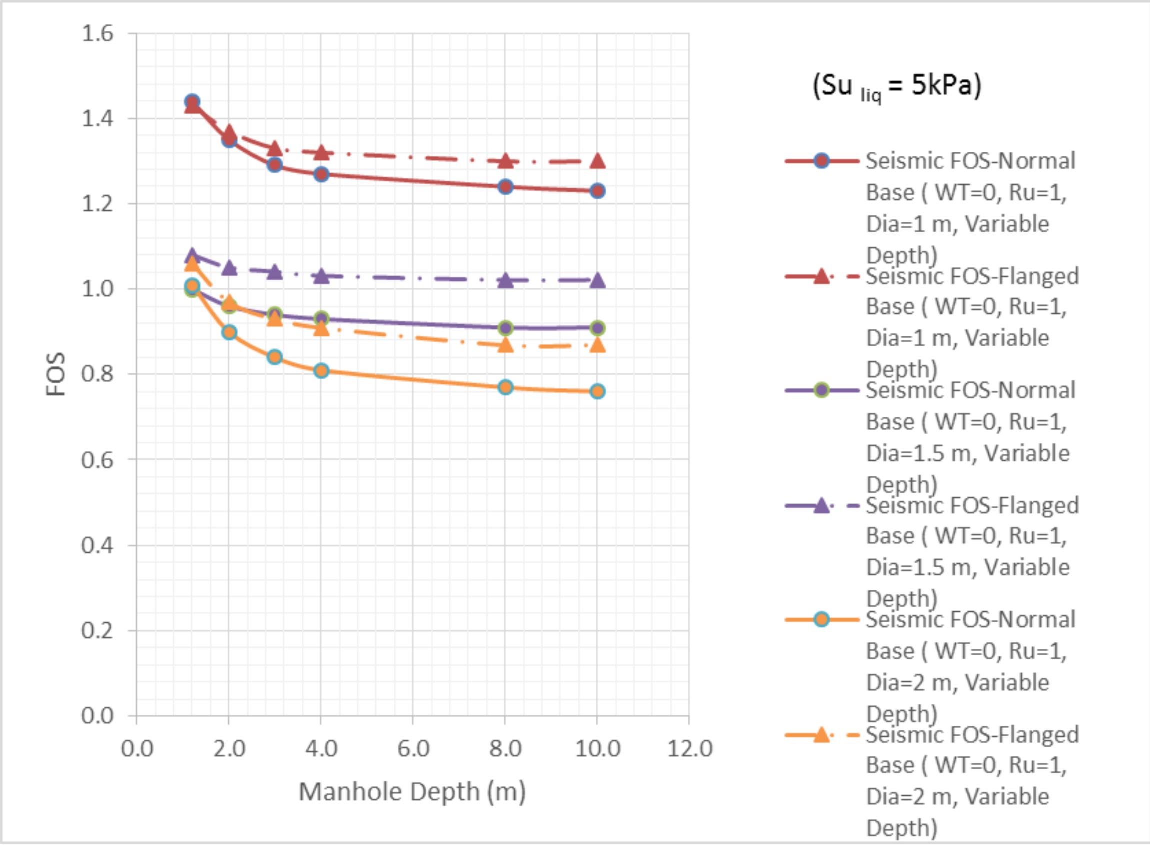


Figure 4-2: Variation of FOS with Respect to Depth at 2m diameter

Liquefied shear strength of soil had a significant impact on FOS.

For soils with liquefied shear strength of 5 kPa, all manholes with a flanged base except the 2 m diameter manhole, produced a FOS of 1 or higher. For soils of liquefied shear strength of 2 kPa and 3 kPa only 1m diameter manholes with a flanged base produced a FOS of greater than 1. For soils with “zero” (0) liquefied shear strength, no manhole arrangement analysed produced a FOS of 1 or higher. FOS for all manhole arrangements in soils with a liquefied shear strength of 0 kPa were between 50 % and 70 %, lower than the same manhole arrangements in soils with a liquefied shear strength of 5 kPa. The FOS for all manhole arrangements in soils with a liquefied shear strength of 2 kPa was between 20 % and 40 %, lower than the same manhole arrangement in soils with a liquefied shear strength of 5 kPa.

FOS generally decreased as diameter increased. FOS for 1.5m diameter manholes was between 20 % and 40%, lower than a 1m diameter of equivalent arrangement. FOS for 2m diameter manholes was between 20% and 45%, lower than a 1m diameter manholes of equivalent arrangement.

FOS was generally found to decrease as depth increased from 1.2 m to 3 m. Depth increases beyond 3 m generally produced a less significant impact on FOS. The decrease in FOS was not proportional with depth. FOS is calculated by a number of variables as discussed earlier. The change in these variables is not linear with depth hence the change in FOS is not linear with depth.

The availability of a flange on the manhole had a significant impact on FOS. A flanged manhole had a FOS between 20% and 80% greater than an equivalent unflanged manhole. The largest increase was observed in 1m diameter manholes in “0” liquefied shear strength soil with 10 m depth.

Generally, the effect of the flange increased with manhole depth. The 20% increase was observed in 2m diameter manholes of 1.2m depth. Generally, the effect of the flange decreased with manhole diameter.

The increase in FOS for the flanged case is governed by the increase in downward resisting force so that the rate of increase in downward force for the flanged manhole is higher than for the equivalent manhole with no flange (Figure 4-3).

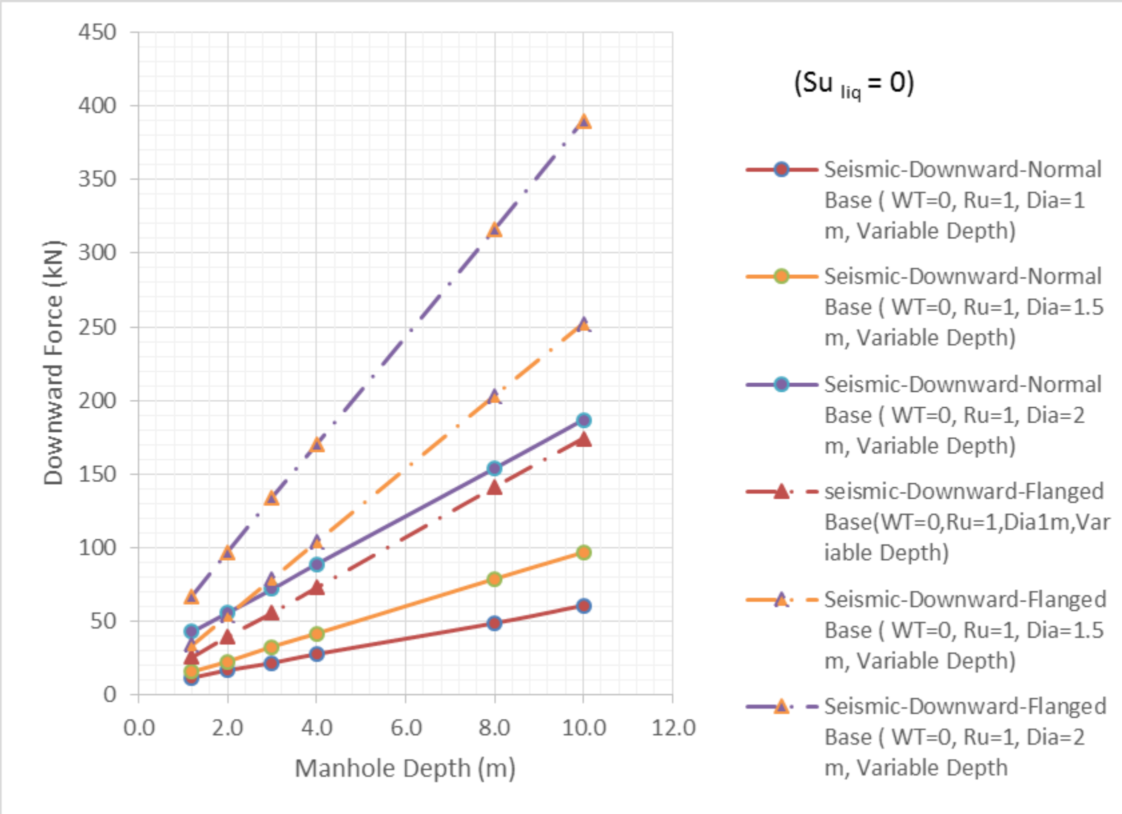


Figure 4-3: Comparison of Downward Force between Manholes with Flanged Base and Normal Base

Figure 4.3 shows that the flange projection helps in increasing the FOS of 1 m and 1.5 m diameter manholes for a given depth. However, beyond a 0.6 m projection length, the increase in FOS is not significant and has therefore been omitted from the plots. It is also likely that a flange larger than 0.6 m would make handling and installation impractical.

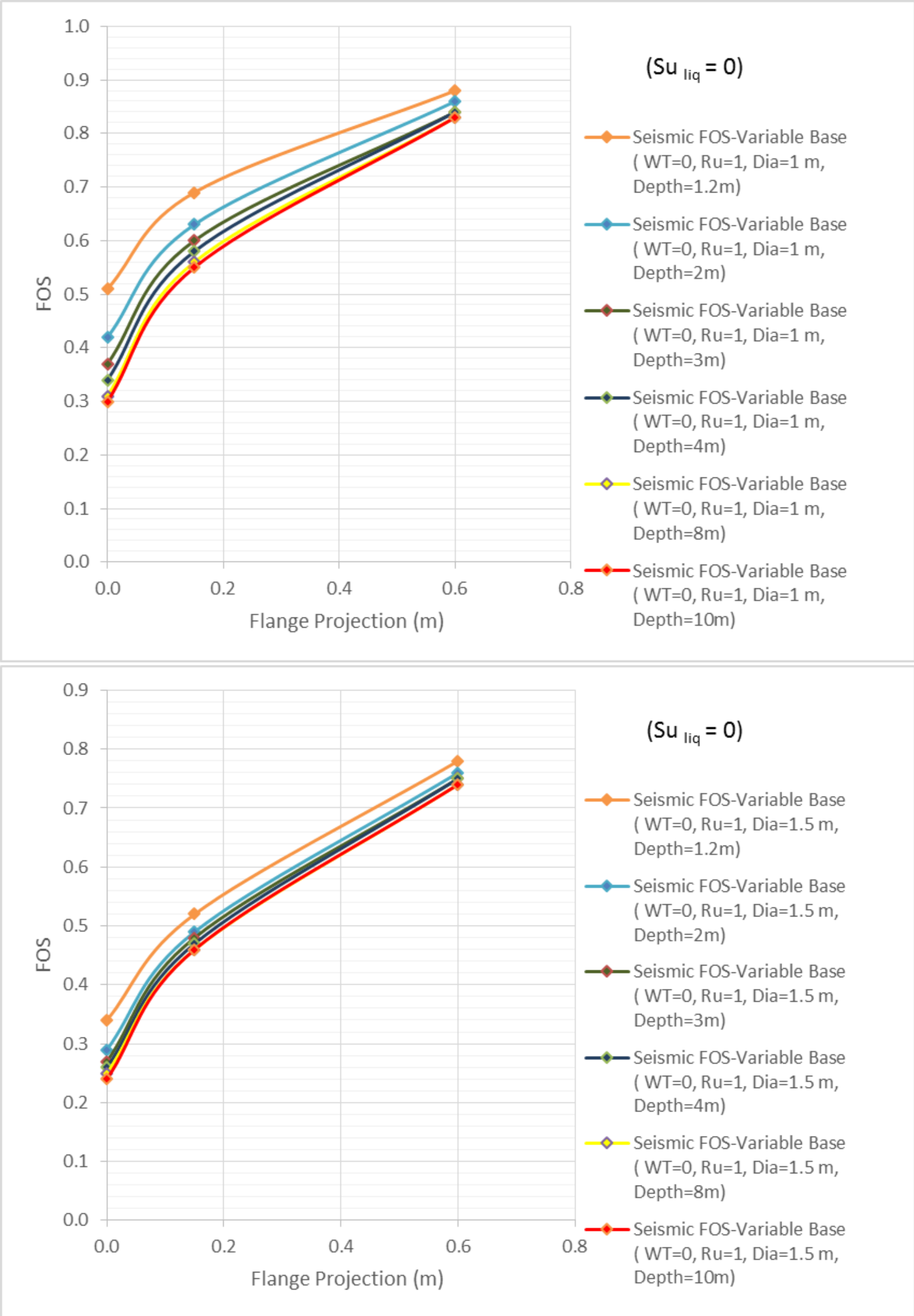


Figure 4-4: Effect of Flange for 1 m manhole (top) and 1.5 m manhole (bottom)

The analysis confirmed that the floatation of a manhole is affected by the following factors:

- Liquefied shear strength of soil
- Availability of a flanged base
- Depth of manhole
- Diameter of manhole

While not investigated in this analysis, it is understood from first principles, literature and professional practice that floatation is also affected by the following factors:

Weight of manhole (calculated from the manhole dimensions in the model) which directly impacts F_T

Depth of water table (assumed to be at ground level in model).

Soil density (assumed to be 18 kN/m^3 in model).

The results show the liquefied shear strength of soil has a significant impact on the floatation of a manhole. This result is supported by Scally (Scally, 2013) who found through parametric analysis that the degree of floatation was correlated to the penetration resistance value obtained by a Cone Penetration Test (CPT). The CPT test values are used to obtain liquefied shear stress using the method developed by Olson (Olson, 2002). Therefore, higher CPT values yield higher liquefied shear stresses.

Soils which are susceptible to liquefaction generally include very loose to loose sand or silt (non-plastic). These soil types are commonly found in New Zealand. As liquefaction occurs, the soil stratum softens, allowing large cyclic deformation to occur. In loose materials, the softening is also accompanied by a loss of shear strength that may lead to large shear deformation. The liquefied shear strength of these soil types has been conservatively assumed to be in the range of 0 to 5 kPa.

Based on the results, 1m and 1.5m diameter manholes in soils with liquefied shear strength greater that 5 kPa will not float provided a flanged base is provided.

For soils with liquefied shear strength of 2 kPa to 3 kPa, only 1m diameter manholes with a flanged base did not float. This represents a generally positive result as the largest percentage of manholes in most networks are 1m diameter with a flanged base. From an inference of the model output, the 1m diameter manhole with a flanged base and a depth of 2 m can be expected to float in a soil with liquefied shear strength of 1.5 kPa.

For soils with liquefied shear strength of “0”, all analysed manhole arrangement floated.

Scally, (2013) found that only 3.5 % of the 1m diameter manholes investigated displayed differential displacement in excess 150mm. D. A. Rowland (2015) postulated that the observed minor differential settlement was better explained by post-liquefaction volumetric reconsolidation of the soil above the foundation level. These studies support the findings that shallow 1m diameter manholes are unlikely to float.

Scally studied the displacement of 1m diameter manholes and square cast in situ manholes. As square manholes are no longer used as standard, the discussion of Scally’s study is limited to circular manholes. Scally assumed that 1m diameter manholes were of the form specified in the Christchurch City Council Standard Details and accordingly included a flanged base. Interpolations from charts provided by Scally indicate approximately 60 % of investigated circular manholes were located in areas which underwent moderate to severe liquefaction.

Of the 14 manholes that experienced displacement in excess of 150 mm, approximately 20 % were located in areas of no liquefaction and 20% low to moderate liquefaction. The remaining approximately 60% were located in areas of high liquefaction. The charts indicate that all manholes that were displaced by more than 150 mm were in excess of 2 m deep. This finding may be due to decreased shear strength associated with intense liquefaction and the increased buoyancy forces in action at higher embedment depths.

The decrease in FOS with increased depth and diameter can be attributed to increased buoyancy pressure. Buoyant forces increase with depth therefore a deeper manhole is subject to higher buoyant forces. A larger diameter provides greater surface area on which buoyant pressures act. This results in greater buoyant forces acting on the base of the manhole. While larger diameters and deeper manholes weigh more and thus generate more resistive force, the increased buoyant forces acting on the manhole are typically of a higher magnitude resulting in lower FOS. The results are supported by findings by Scally (Scally, 2013) which determined that manholes with lower embedment depths experienced a lesser displacement.

It should be noted that these results represent full liquefaction of the full soil depth in line with the conservative testing philosophy. In reality, partial liquefaction and liquefaction of the partial depth can occur. With partial liquefaction, the soil will retain a higher proportion of its shear strength compared to full liquefaction. This is in line with findings by Scally (Scally, 2013) which confirmed that manhole displacement is related to the severity of liquefaction. Liquefaction of partial soil depth will result in lower buoyant forces. The presence of a low water table or impermeable soil strata can result in liquefaction of partial soil depth.

5 Floatation Mitigation Measures

As the results indicate, floatation is influenced by a number of factors, therefore floatation mitigation measures encompass a number of approaches.

Ideally, manholes should be located in ground that is not liquefiable as this gives the greatest protection against floatation. However, this is not possible in many cases and alternative methods of mitigating floatation needs consideration.

Priority should also be given to reducing the size and depth of manholes in areas where there is potential for liquefaction. The overall arrangement of the drainage network should be designed to reduce the size and depth of manholes. Depth is determined by the topography of the ground and the need to provide adequate grade or clearance to other infrastructure. Size is generally determined by the number and size of connections the manhole services. These elements may be influenced by overall design philosophy to reduce conditions that increase susceptibility of floatation.

Following the 1995 Kobe earthquake, the Kobe Municipal Waterworks Bureau developed various methods to mitigate the floatation of manholes (Misko Cubrinovski, 2011). A preliminary review of the measures is presented below and covers the appropriateness of the proposed measures for use in New Zealand.

System Name	Description	Preliminary Review Comments
Earth drain method	Artificial drain consisting of high permeability soil is placed around the manhole using a specialized machine.	Suitable. Similar design trialled by SCIRT. Refer Well Graded Backfill section below.
Anchor wing method	The manhole is anchored to the bottom unliquefied layer by a frame structure (called wing).	Detailed information not available after literature search.
LAM Method	The manhole is anchored to the bottom unliquefied layer by a single rod attached to the bottom of the structure.	Detailed information not available after literature search.
Safe Manhole Method	Tubes are installed within the manhole and near the joint to drain excess pore water pressure generated during liquefaction.	Similar methods available via the use of proprietary products. Refer Pressure Dissipation Devices below.
Anti-float method	A heavy base plate is placed at the bottom of the manhole to prevent uplift.	Method may be suitable for critical manholes that are susceptible to liquefaction.
Aseismic method for existing manholes	An specialised machine will cut through the manhole walls and flexible joints of the existing pipe. Following this elastic sealant are installed at the connection.	Method does not prevent floatation. Instead, greater flexibility is provided in the connection to reduce damage.
Aseismic improvement method for existing pipe	Using a specialised cutting machine, the pipe joint is removed. Then a light composite rubber /steel fitting is installed to make the joint flexible.	Method does not prevent floatation. Instead, greater flexibility is provided in the connection to reduce damage.
Prevention of uplift using manhole flange	A convex-shape material is placed on the outer part of the manhole, and a weight is placed to increase resistance against uplift.	Similar method is currently specified in the New Zealand Standards (Standards New Zealand, 2010). Refer Flanged Base section below.
Float-less method (non-excavation type)	Excess pore water pressure generated by earthquake is drained out.	Similar methods available via the use of proprietary products. Refer Pressure Dissipation Devices below.
Magma lock method	The impact of earthquake-induced displacement is decreased using a special flexible joint and magma lock.	Detailed information not available after literature search.
Hat ring method	A cylindrical ring block is placed on existing manhole to prevent uplift.	Detailed information not available after literature search.

System Name	**Description**	**Preliminary Review Comments**
Wide safety pipe method	Tubes installed inside the manhole dissipates the excess pore water pressure. Ground water is prevented from entering the manhole by using a reverse-action valve in the manhole pipe.	Similar methods available via the use of proprietary products. Refer Pressure Dissipation Devices below.
"Mr. Aseismic" (Taishin-ippatsu kun) method	New pipes are installed to add seismic capacity to old structures with worn-out pipes and manholes	Method does not prevent floatation.

Table 5-1: Evaluation of Floatation Mitigation Measures Proposed After Kobe Earthquake

The following mitigation measures are appropriate for use on new manholes and generally conform with the practices described in NZS 4404:2010.

5.1 Flanged Base

The inclusion of a flanged base is a relatively simple mitigation measure that is already specified in NZS 4404: 2010. The analysis found that the inclusion of a flange improved the FOS by 20% to 80%. The results of the analysis demonstrated that a flanged base prevented a 1m diameter manhole from floating in 2 kPa (or greater) liquefied shear strength soil.

A typical flange extends 150 mm beyond the external face of the wall. The analysis showed that a typical flange could not prevent floatation of a manhole in "zero" liquefied shear strength soil. Further analysis using the model suggests that an enlarged flange extending up to 600 mm would increase the FOS close to 1 for 1.5 m and 2 m diameter manholes. However larger flanges do not appear to produce a noticeable benefit and would probably hinder handling and installation.

The self-weight of soil above the projected area of the extended flange base of the manhole aids in increasing the resisting force. In addition, the resisting shear area of the manhole with a flanged (projected) base is greater than with the manhole with an unflanged base. These result the overall FOS for the manhole with a flanged base being greater than for the manhole with an unflanged base.

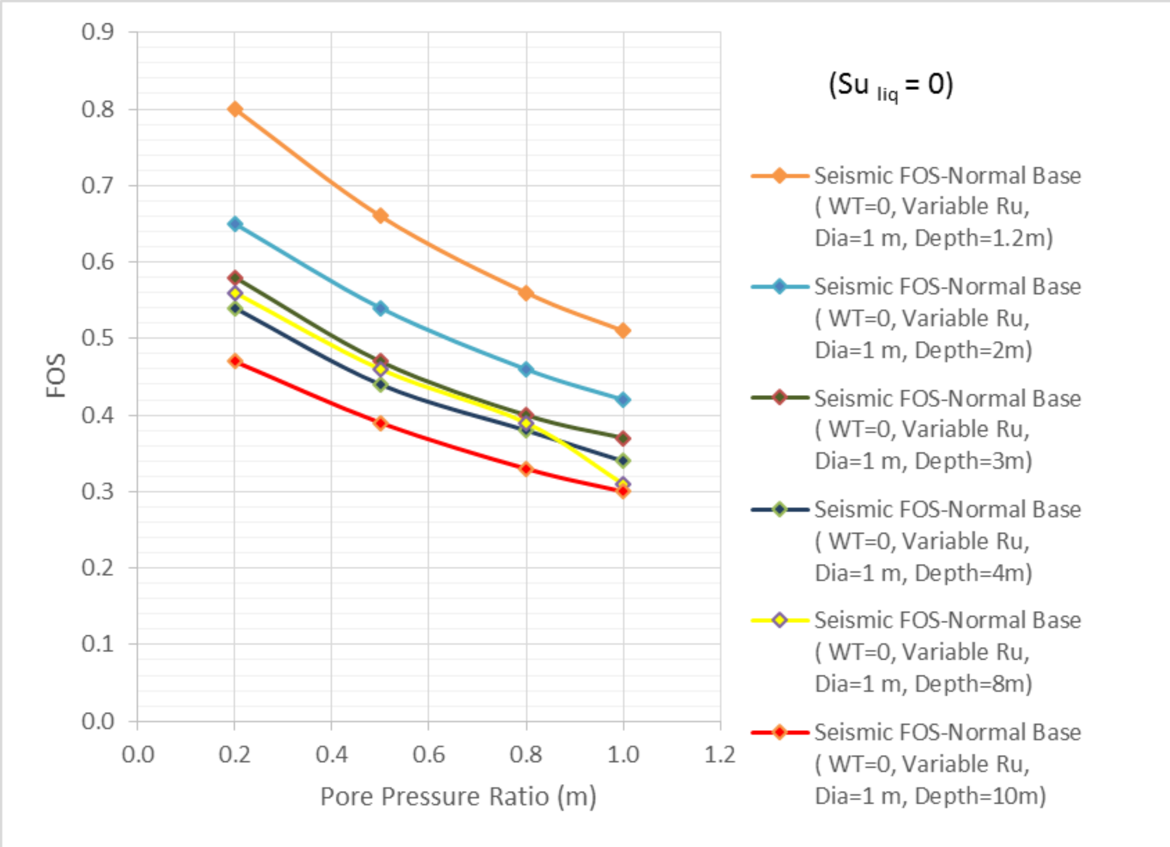
5.2 Well Graded Backfill/Permeable Backfill

In this mitigation, permeable, well graded backfill is placed around the manhole. The mitigation measure works on the principle of allowing pore water to dissipate thereby reducing buoyant forces and minimising the loss of shear strength.

A full scale field trail was conducted to determine whether the proposed amendments functioned as designed. The trial consisted of simulating an earthquake using explosives on a number of manhole arrangements.

The trial and subsequent findings are presented in D.A. Rowland, 2015. The trial included testing the impact of well graded backfill (CCC AP65) on floatation of the 1m diameter, flanged, concrete manhole. The well graded backfill attenuated excess pore water pressures and did not liquefy. Pore water pressure in the well graded backfill was measured to be less than 30% that of the pore water pressure in the insitu soil. The authors of the study caution the validity of the results until further works is completed to better understand the performance of the well graded backfill. However, the measured results align with the theoretical behaviour of well graded backfill.

Our analysis indicated that the FOS of a manhole is governed by the pore water pressure variation. It has been observed that the rate of increase in FOS (for both normal base and flanged base manholes) is around 50% to 60% when the pore water pressure ration decreases from 1 to 0.2. Figure 5-1 provides the typical trends of FOS variation for different pore water pressure ratios analysed. It implies that backfill material with well graded permeable material would aid in quick dissipation of pore water pressure during seismic shaking, thereby increasing FOS.



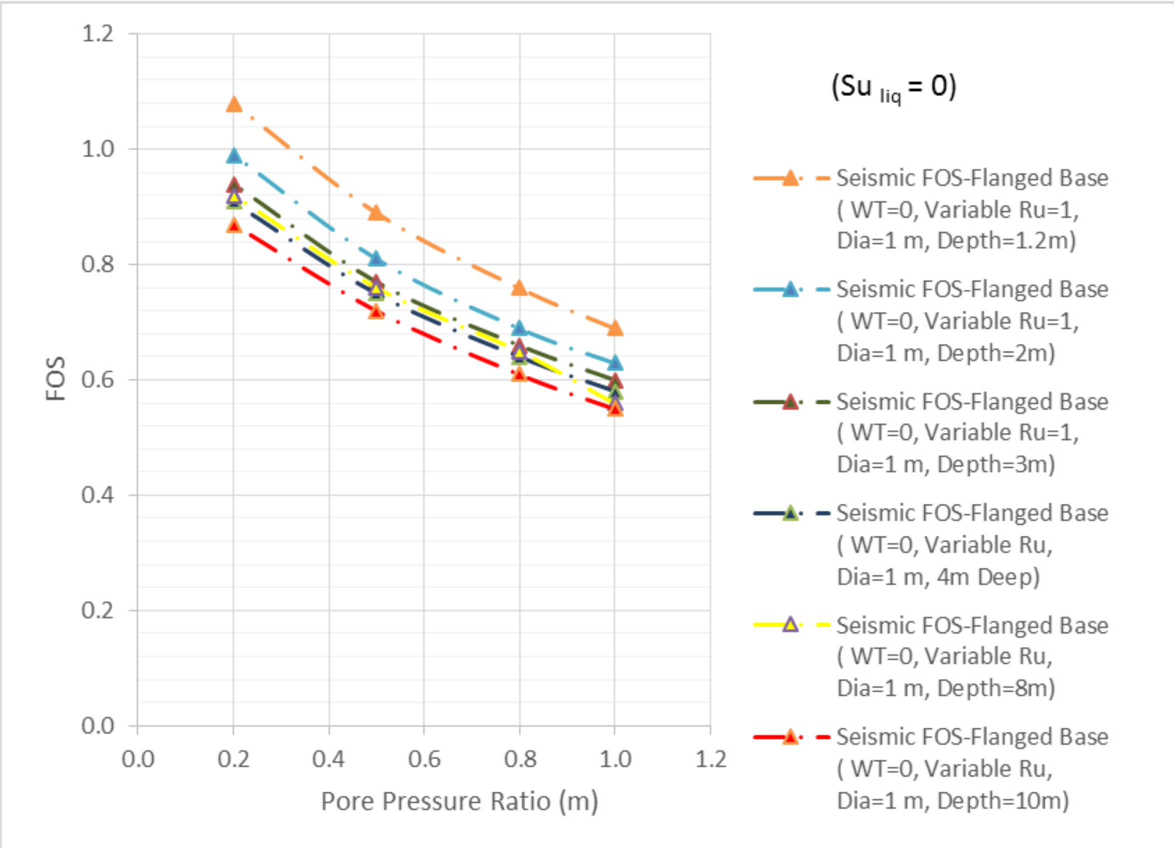


Figure 5-1: Effect of Flange Projection on the FOS

5.3 Increased Base Thickness / Weight of the Manhole

Another mitigation measure is increasing the base thickness of the manhole thereby increasing the overall downward force resisting against the floatation. Figure 5-2 shows the plots of FOS variation with respect to an increase in base thickness of manholes (normal base and flanged base). However, it is to be noted that this option could be combined with the increased flange width option to avoid bearing capacity failure. The increased flange width would help in distributing the loads to the wider area.

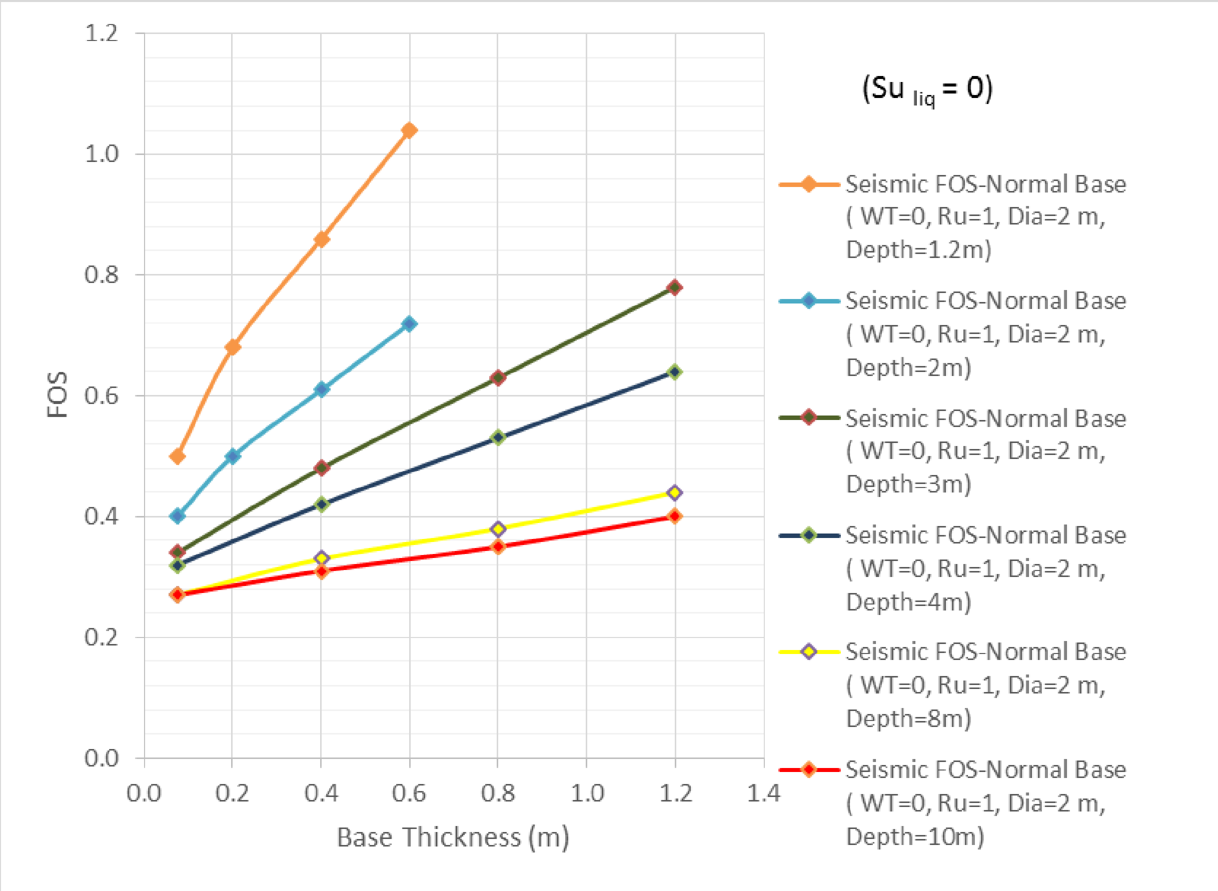
The following mitigation measures are appropriate for use with existing manholes.

5.4 Pressure Dissipation Devices

Pressure dissipation devices such as valves and tubes function by allowing excess pore pressure to dissipate without leading to excessive buoyancy forces on the manhole. These devices are generally installed into the wall of the manhole and are in contact with the surrounding soil. Ingress of soil is prevented by fine screen mesh integrated into the device. Numerous proprietary pressure dissipation valves are available in the market. They can be retrofitted to existing manholes.

Pressure dissipation valves have seen extensive use in Japan. A case study of manholes fitted with proprietary dissipation valves was undertaken following the 2011 Great East Japan Earthquake. The study focused on Shinibika Township, Ishimaki City and Higashimatsujima City which were all subject to liquefaction. The study found that there was no floatation of manholes that were fitted with dissipation valves. Neighbouring cities which did not employ dissipation valves reported widespread manhole floatation after the liquefaction event. (Hynds Pipe Systems Ltd).

Pressure dissipation valves are typically not required as most manholes are not at risk of floatation. However, pressure dissipation valves may be appropriate if site assessments find that the manhole is at risk of floatation and/or is of high criticality.


(Su liq = 0)
FOS
Base Thickness (m)
Seismic FOS-Normal Base (WT=0, Ru=1, Dia=2 m, Depth=1.2m)
Seismic FOS-Normal Base (WT=0, Ru=1, Dia=2 m, Depth=2m)
Seismic FOS-Normal Base (WT=0, Ru=1, Dia=2 m, Depth=3m)
Seismic FOS-Normal Base (WT=0, Ru=1, Dia=2 m, Depth=4m)
Seismic FOS-Normal Base (WT=0, Ru=1, Dia=2 m, Depth=8m)
Seismic FOS-Normal Base (WT=0, Ru=1, Dia=2 m, Depth=10m)

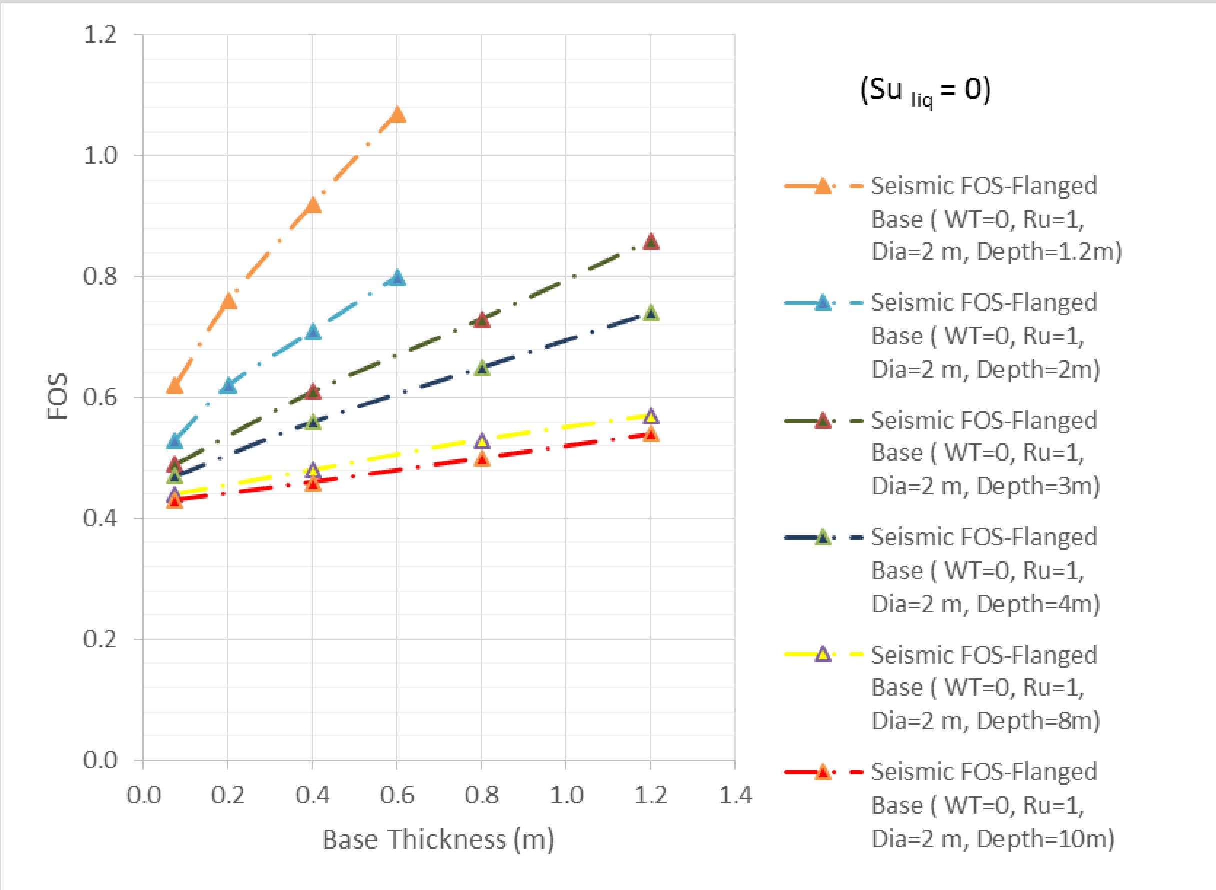

(Su liq = 0)
FOS
Base Thickness (m)
Seismic FOS-Flanged Base (WT=0, Ru=1, Dia=2 m, Depth=1.2m)
Seismic FOS-Flanged Base (WT=0, Ru=1, Dia=2 m, Depth=2m)
Seismic FOS-Flanged Base (WT=0, Ru=1, Dia=2 m, Depth=3m)
Seismic FOS-Flanged Base (WT=0, Ru=1, Dia=2 m, Depth=4m)
Seismic FOS-Flanged Base (WT=0, Ru=1, Dia=2 m, Depth=8m)
Seismic FOS-Flanged Base (WT=0, Ru=1, Dia=2 m, Depth=10m)

Figure 5-2

6 Conclusion/Recommendations

Based on the analysis, floatation of manholes is not considered a major problem in most situations. The differential displacement of manhole and surrounding ground observed after the CES (and other major earthquakes) is likely to be due to settlement of the ground. This finding is supported by the work of Scally, 2013 who found only 3.5% of 1m diameter manholes in liquefiable soil exhibited differential settlement in excess of 150mm.

The analysis found that large diameter and deep manholes, and manholes located in low liquefied shear strength soil are more prone to floatation. FoS generally decreased as diameter and depth increased. All manhole arrangements in soil with liquefied shear strength of 0kPa floated while the majority of manholes in soils with liquefied shear strength greater than 5kPa did not float. 1m diameter manholes were found not to float in soil with 2kPa liquefied shear strength provided a flange was available.

The analysis confirmed that the flanged base specified in NZS 4404:2010 (extending 150mm beyond manhole wall) is beneficial in minimising floatation. The availability of a flanged base was shown to improve the FOS by 20% to 80%. As such it is recommended that the flanged base continue to be specified. The analysis found that floatation of manholes can be improved by adopting larger bases and well graded backfill materials. Further investigation is advised to determine the feasibility of the above options in detail in order to support our analysis.

In order to mitigate floatation of new manholes, it is recommended that manholes be located in non-liquefiable soil, and be made as small a diameter and as shallow as possible.

In order to mitigate floatation of existing manholes, pressure mitigation valves can be fitted into the manhole wall. However, this is not appropriate or cost effective for all manholes in potentially liquefiable soils and a preliminary assessment for suitability is recommended.

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