Appendix L

Liquefaction Induced Lateral Spreading Mitigation

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L1.1 Introduction

The extent of lateral spreading has been assessed using the Bartlett and Youd (1992, Kramer) approach for Pegasus Bay Township without adequate mitigation measures. Large areas of the proposed township could experience large ground displacements when both the 150 year and 475 year return period earthquakes occur caused by liquefaction induced lateral spreading. The exact displacements at varying locations around the lake are described below.

Progressing from the ‘Seismic Liquefaction Study of Pegasus Bay Town’ July 2001, URS has evaluated the Lateral Spreading potential for varying seismic events. The same methods as in the 2001 report i.e. the cyclic stress ratio and the energy method were used to identify the depth and thickness of liquefiable layers and also used to estimate the potential magnitudes of lateral spreading displacements around the lake at Pegasus Bay Township.

L1.2 Method Used

L1.2.1 Bartlett and Youd

The Bartlett and Youd approach has developed two empirical models for sites near steep banks and sites on gently sloping ground. The two models were developed from a large database of lateral spreading case histories where regression analysis was used to identify factors that most strongly influence the lateral spreading displacements.

Both models use information about the thickness, grain size and average fines content of the liquefied granular layers, the intensity of the earthquake and the horizontal distance from the site to the source of the earthquake. The model used for sites near steep banks, the *free face model*, incorporates an additional parameter, a ratio between the distance from the site to the bank and the height of the bank. The *sloping ground* model uses the slope of the ground profile as the additional parameter.

Our lateral spreading analysis used the free face model to generate ground displacements around the lake if no remedial measures were undertaken. This models the impact of creating the lake on removing a portion of the lateral stabilizing force, resulting in ground movements exceeding the acceptable limits of 250mm to ensure utilities remained in service. Ground displacements exceeding 500 mm are found within 80 metres of the lakeshore increasing to 1 metre displacements within 30 metres of the lakeshore for the design 150 year return period earthquake.

The 475 year return period earthquake was then analysed, showing approximately 8-10 times more movement than the design event. This created displacements of 0.25 metres, 0.5 metres and 1.0 metres at 1800 metres, 620 metres and 220 metres from the lakeshore, respectively.

Movement (mm)	Distance from Lakeshore for 150 yr event
250	220 m
500	78 m
1000	27 m

Table 1: Summary of the lateral displacement experienced at certain distance from the Lakeshore for the 150 yr event using Bartlett and Youd's approach.

Buttressing around the lakeshore was investigated as a remedial measure (L1.3 Remedial Measures) to replace the restraining action of ground removed by creating the lake. The method would be to locally increase the soils shear strength and density. We now apply this *sloping ground* model as the buttressed lakeshore acts to restrain lateral spreading eliminating the free face for the liquefied soil to spread towards. Instead it is restrained by the shear strength of the compacted soil buttress, which allows the *sloping ground* model to be applied.

L1.2.2 Slide

SLIDE is a 2D slope stability program for evaluating the stability of circular or non-circular failure surfaces in soil or rock slopes. External loading (such as seismic and vertically distributed loads), groundwater and support can all be modeled in a variety of ways. Slide was used to analysis the stability of the site at Pegasus Bay once the lake was excavated and filled with water. It was also used to generate an understanding of what factors of safety would be provided from the ground under different scenarios during and after the design earthquakes.

A model of the site was created using cross-sections A, C and J (drawing G005, G006 and G009), the ground profile, subsurface layering of soils, groundwater depths and soil properties. The CPT data and the liquefaction assessment of the site (Appendix K), was added to the model incorporating the depth and thickness of the most relatively continuous liquefiable layers, as a whole, across the site. The two most significant layers found around the lake are 1.5–2.6 and 3.3-3.5 metres below the existing ground surface, producing a total liquefiable layer thickness of 1.3 metres. It must be noted that other isolated pockets of liquefiable sand present at other depths within this area exist and are also likely to liquefy during the design 150 year return period earthquake and experience some vertical settlement. However these pockets are discontinuous and not expected to contribute to the liquefaction induced lateral spreading around the lake of Pegasus Bay Town.

This model was first simulated (scenario #1) by being seismically loaded with both the 150 and 475 year return period earthquakes where the lakeshore was observed to fail. The analysis showed instability (FOS<1.0) up to 44 metres from the lakefront, with a minimum FOS of 0.713, when seismically loaded with the 150 year return period earthquake. This failure occurred with the existing soil properties, prior to the rapid decrease in shear strength during liquefaction. Failure at this stage of the event was unexpected and shows that movement of the ground is possible before the soils liquefy.

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A second scenario was analysed after the earthquake had finished and the sands had liquefied, reducing any liquefied layers soil shear strength completely. We assigned soil properties (c = 1, Phi =0) estimated from case histories of liquefied sandy soils and ran the model without seismic loading. This is done because the majority of the soil shear strength is lost after the earthquake has finished. The liquefied layers can effectively act as a fluid possessing no shear strength. It is at this stage of the event that flow failure and lateral spreading is predicted to occur. The proposed failure plane was placed in *slide* at the top of the liquefied sand layer because of void redistribution of the layer during liquefaction. Failure was observed in the same region around the lakeshore however these instabilities only existed (FOS<1.0) up to 20 metres from the lakefront (shown in 'Scenario #1'). This is because slide conservatively evaluates the length of ground that will be unstable, as it was not designed specifically to model flow failures.

A third scenario was created incorporating a 10 metre wide compacted soil buttress around the lakeshore of the site, extending 20 metres into the base of the lake. This was incorporated as a remedial measure to prevent lateral spreading into the lake. The slide analysis showed the stability of the ground to increase significantly when this compacted buttress of sand was provided around the sides of the lake. The factor of safety jumped from 0.815 to 2.3. As discussed below in the "Remedial Measures" section, buttressing around the lakeshore with compacted sand is recommended to control lateral spreading at Pegasus Bay.

This third scenario was applied to 'Bartlett and Youd' second model (*sloping ground*) for calculating lateral spreading displacements. This model can now be applied to the site as the compacted soil buttress effectively removes the free face at the lakeshore and treats the site as having a gentle sloped ground profile. This assumption can be made as the compacted soil buttress provides shear strength to the ground that is effectively removed by the free face. This third scenario generated much lower displacements than the first model, suggesting the buttressing would be an effective method of reducing the lateral spreading problem at Pegasus Bay. The lateral displacements expected from the buttressed site were 0.125m and 0.460m for the 150 year and 475 year return period earthquakes respectively. This level of movement is considered acceptable, as the effect on utilities is not expected to prevent them from being serviceable.

L1.3 Remedial Measures

The existing ground profile of the site consists of 'medium dense sands' when saturated are very susceptible to liquefaction. One method to prevent liquefaction from occurring in these soils is to strengthen the sands by densification. By increasing the density of the saturated sand, the void ratio decreases, reducing the amount of settlement/densification and liquefaction susceptibility of the sand layer.

Densification of sand layers can be done by one of the following ways.

1) Dynamic compaction, where a heavy weight is dropped from height onto the ground surface to compact loose soils and sands. Dynamic Compaction can remove potential liquefaction layers to depths exceeding 6 metres. Below this depth the effect of any liquefiable layers at this site will be minimal and significant displacements eliminated.

2) Vibro floatation is the process where a vibrating probe is inserted into the ground to cause the compaction of sands.

3) Inserting stone columns into the ground is another technique used to strengthen weak soils and reduce the liquefaction potential of weak layers. This technique involves inserting a probe (similar to that used for vibro flotation) into the ground. The probe penetrates the ground using its own self weight and vibrating energy and is driven down to the stone columns specified depth. Once at this depth it is withdrawn in steps (lifts) of 1m and the hole is backfilled with gravel. The probe is then reinserted into the gravel backfill, compacting it into the surrounding soil and expanding the stone column diameter. The process is repeated across the site, in a grid type pattern, increasing the strength of the soil and removing potential layers of liquefaction.

4) Excavation and then re-compaction of loose sand is another way to create a denser soil structure. The sand will be re-compacted in layers to ensure all the sands are compacted to the desired density. The problems of using this method at Pegasus Bay is the relatively high water table that will create difficulties excavating to the depth of some of the loose and potentially liquefiable layers. This method is a lot cheaper than the dynamic compaction, however its effectiveness at depth is limited.

L1.3.1 Buttress

This first option to prevent lateral spreading from the site at Pegasus Bay will involve dynamic compaction (or excavation and re-compaction) around the lakeshore. A compacted buttress of high density sand around the lake front will prevent liquefaction within the area compacted and contain/eliminate any lateral displacements of soils towards the free face of the lake. Using the slope stability model '*slide,*' the size of this buttress is recommended to be 10 metres wide and extend a future 20 metres into the lake. The depth of compaction is recommended to extend 5.5 m below the ground surface.

L1.3.2 Stone Columns

Stone Columns could be used to prevent lateral spreading at Pegasus Bay. Although this method will not remove susceptible liquefaction layers, it will isolate these layers by very dense columns of gravel that will eliminate the potential for lateral spreading. The problems with this method will be the cost involved in treating such a large area in this way. Stone columns at this site will be an expensive remedial and this method is not recommended for Pegasus Bay.

L1.4 Vertical Settlement

Vertical settlement will still not be eliminated unless ground compactions in completed across the whole site and all liquefiable layers are compacted. Although this could be practically achieved, it is not recommended to be economically beneficial. Instead Dynamic compaction or excavation and re-compaction of the lakeshore and road foundation where services will be located will be a better option.

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By compacting all the road foundations a grid of high density soils around the site is estimated to minimise and isolate liquefaction (lateral displacements) to an acceptably level so utilities will remain in service after a 475 year return period earthquake.

The estimated settlements in the residential areas are expected to be less than 100 mm for the 150 year return period earthquake (refer to drawings in appendix K). As discussed in the ‘Seismic Liquefaction Study of Pegasus Bay Town’, prepared in 2001 by URS, it is recommended that residential house foundations should be detailed to resist liquefaction effects and prevent large-scale damage to these structures. Slab-on-grade foundations were found to effectively prevent extensive damage in the 1994 Northridge Earthquake in California and are recommended for single-dwelling family homes.

L1.5 References

S L Kramer (1996) Geotechnical Earthquake Engineering, chap9 & 10

URS (NZ) Ltd. (2001) *Seismic Liquefaction Study of Pegasus Bay Town*

R B Seed, K O Cetin (2003) *Recent Advances in Soil Liquefaction Engineering A Unified and Consistent Framework*, 26th Annual ASCE Los Angeles Geotechnical Spring Seminar.

L1.6 Slide Figures

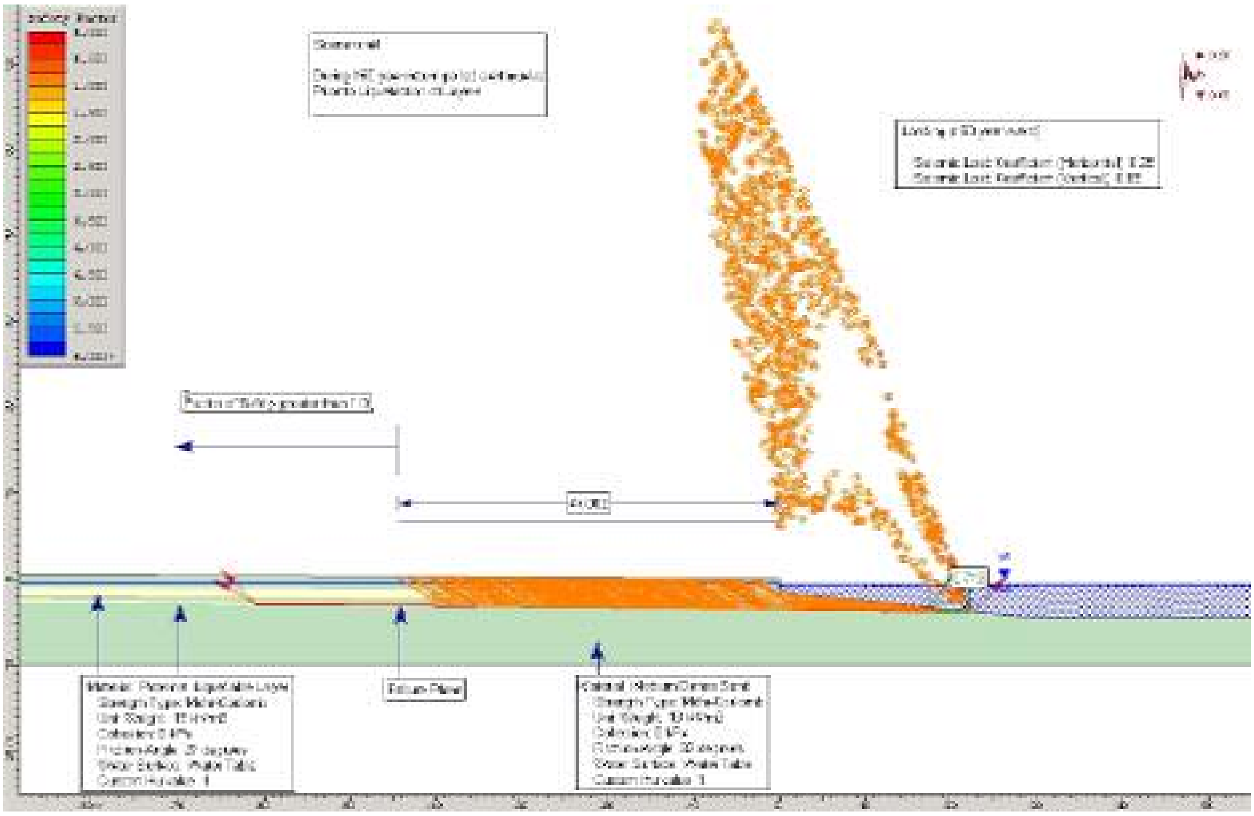

Figure 1: Scenario 1, failure during 150 year return period earthquake, prior to liquefaction.

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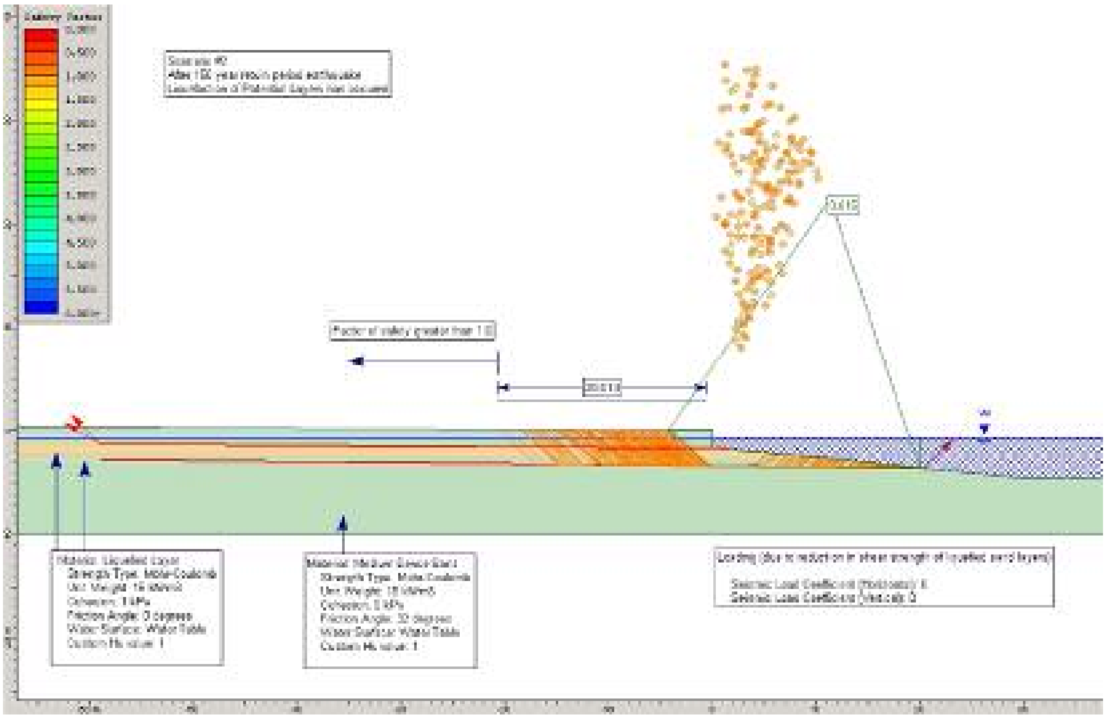

Figure 2: Scenario 2, failure after 150 year return period earthquake, after liquefaction of sand layers

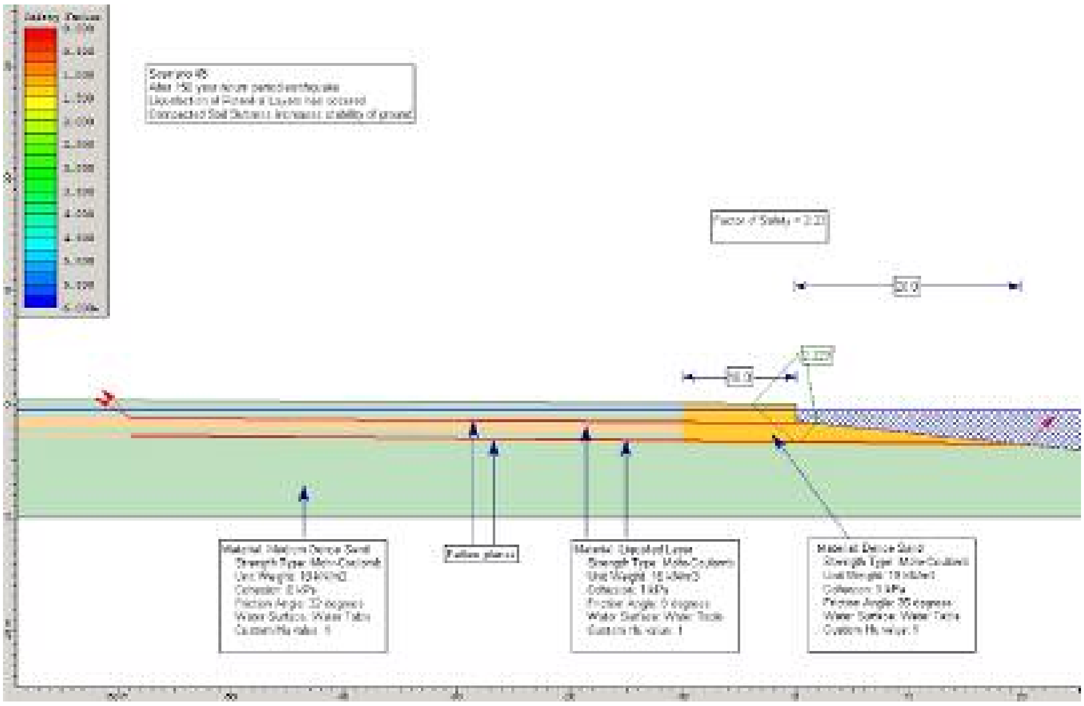

Figure 3: Scenario 3, FOS = 2.3 after liquefaction from 150 year return period earthquake compacted toe buttress