Validation of design on a site subject to seismically induced ground movement

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ABSTRACT

The site considered is near the town of Kawerau (New Zealand) within in the seismically active Taupo Volcanic Zone (TVZ). The site is underlain by recent, pumiceous and scoriaceous gravels and sands. Analyses indicated that these deposits could be subject to liquefaction, seismically induced settlements and possibly lateral spreading. The records of performance of the area during the Edgecumbe Earthquake (Mw 6.5, 1987) are employed to validate behaviour predictions.

1 GEOLOGY AND SOIL PROFILE

The site is located on a terrace set around 100m from the Tarawera River. Published geological maps (Nairn, 2000) show that the site is located within the Whakatane Graben (part of the TVZ) and indicate that the site is underlain by geologically recent re-deposited ash and scoria from Tarawera and Rotomahana Pyroclastics (T&RP), emplaced 120years ago and Kaharoa Pumice Alluvium (KPA), estimated to have been emplaced around 700 years ago. The typical soil profile encountered during the site investigation is summarised in Table 1. Groundwater levels at the site are approximately 6m below ground level (BGL), around 0.4m above the river water level.

Table 1: Typical Soil Profile & Geotechnical Properties

Geologic Unit	Layer	Depth To Top (m)	SPT N Range	Density (kN/m^3)	Fines (%)	Plastic Index
T&RP	Pumice gravel and sand (COARSE ALLUVIUM)	0	2 – 5	16.5	<10	N/A
KPA	Pumiceous gravelly sand (UPPER PUMICE ALLUVIUM)	2.0 – 2.5	6 - 47	17.5	<10	N/A
	Pumiceous silty sandy gravel (IGNIMBRITE)	19 - 22	5 - 47	19	>35	N/A
	Silt (AIRFALL DEPOSIT)	21 - 22	5 - 19	15.5	>75	9-12
	Pumiceous sand, trace gravel (LOWER PUMICE ALLUVIUM)	21.5 - 25	21 - 43	17.5	<10	N/A

2 SEISMICITY

Kawarau (Figure 1) lies within a tension zone associated with the junction of the Pacific and Australian plates known as the Taupo Volcanic Zone (TVZ). The TVZ extends from Mt Ruapehu, through Taupo and Rotorua to White Island. The seismicity of this area is dominated by normal faulting orientated NE/SW. On the 2nd of March 1987 a Magnitude (Mw) 6.5 earthquake occurred at a depth of 10 km with the epicentre near the town of Edgecumbe approximately 15 km north of Kawerau. Peak ground accelerations are estimated to have been in the order of 0.3g in Kawerau (BCHF 1987). This level of shaking can be related to a probabilistic return period and the design shaking levels a proposed development by the Structural Loadings Code (NZS 1170.5: 2004).

Table 2: Comparison of Seismic Loading

	Edgecumbe Earthquake	Example Serviceability Earthquake (SE)	Example Design Basis Earthquake (DBE)
Return Period	250y	25y	1000y
Peak Ground Acceleration	0.3g	0.1g	0.5g

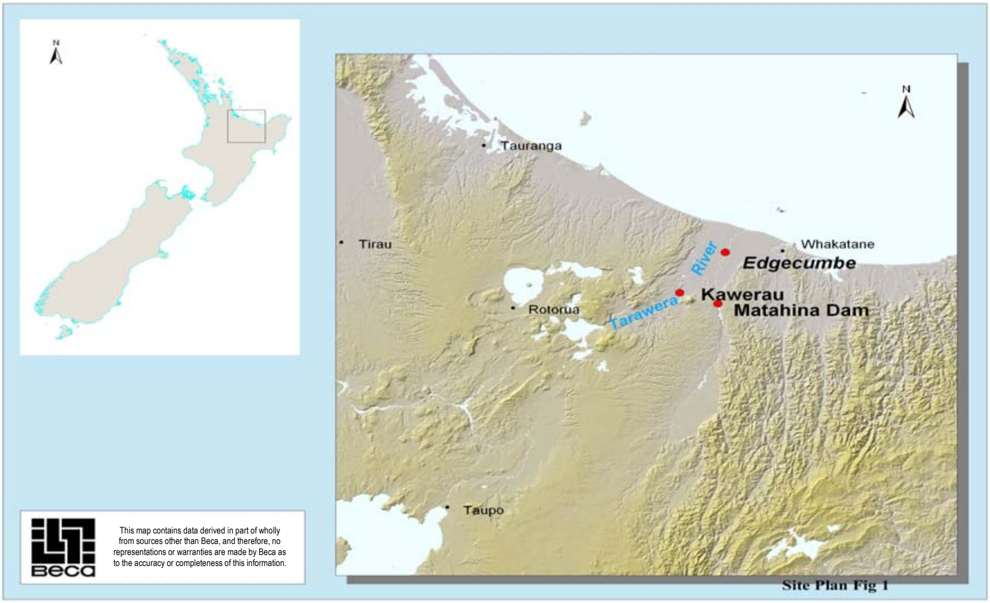

Figure 1: Site Plan

3 LIQUEFACTION POTENTIAL

The age,low density of the underlying sediments and observations during the Edgecumbe Earthquake (Beca Carter Hollings & Ferner, 1987) suggest that the soils underlying the site have a low resistance to liquefaction. Analyses were therefore carried out to provide estimates of the likely extent of liquefaction and to identify any related issues for the site under the design shaking levels.

Soils encountered on site have been assessed against accepted criteria defining liquefaction susceptibility based on soil grading and plasticity (Andrews and Martin, 2000) and followed by an assessment carried out using the 'simplified procedure' (NCEER, 1997). The results of analyses are presented in the geological cross section (Figure 2). SPT tests where liquefaction is considered likely to occur in DBE level shaking have been circled on the cross section. The results can be summarised as follows:

- Liquefaction is not likely to occur above a depth of 6m, as the soil is unsaturated.
- Liquefaction is not likely to occur below 6m depth during the Serviceability Earthquake
- Under the design basis earthquake liquefaction is likely to be relatively widespread within the Upper Pumice Alluvium with localised liquefaction potentially occurring also in the Lower Pumice Alluvium and non-plastic zones of the Airfall Deposits.

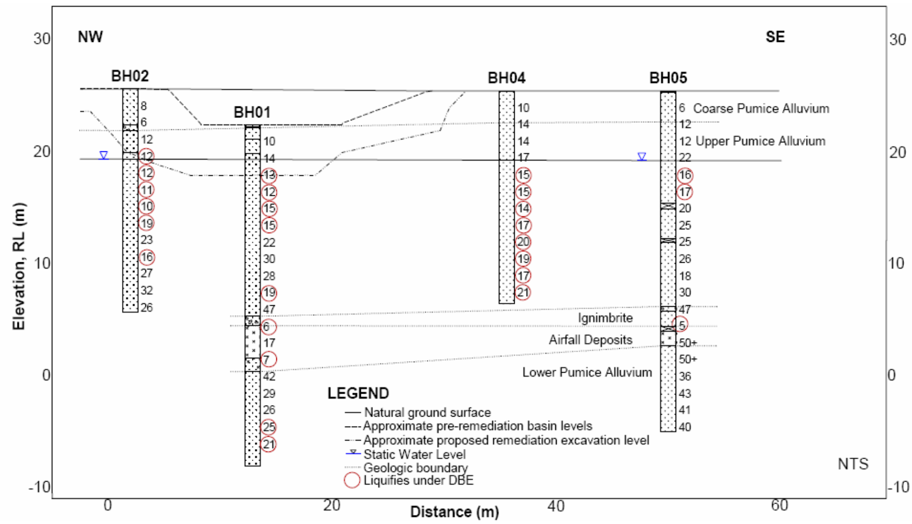

Figure 2: Cross Section through site

4 SEISMIC SETTLEMENT

4.1 Predicted Seismic Settlements

Seismically induced settlement was assessed based on published empirical correlations (Tokimatsu and Seed: 1987) Due to the presence of loose sands above and below the water table both liquefaction induced settlement and dry sand compaction effects are considered. Analysis has also been carried out for levels of shaking corresponding to the Edgecumbe event to allow comparison to observed behaviour. Predicted settlements are summarised in Table 3.

Table 3: Predicted Settlements

Case Considered		Edgecumbe- 0.3g	SE-PGA 0.1g	DBE- PGA 0.5g
Dry sand compaction	Range	<25 - 50mm	-	<25 - 99mm
	Mean	<25mm	<25mm	70mm
Liquefaction induced settlement	Range	<25 – 129mm	-	104 - 235mm
	Mean	47mm	<25mm	150mm
Total	Range	<25 – 148mm	-	152 – 315mm
	Mean	62mm	<25mm	215mm

4.2 Observed Seismic Settlements

Displacements were recorded at a number of locations around the area and within the adjacent industrial facility including nearby survey benchmarks, at the Apprentice Training Centre (ATC) and at a pipe bridge where the soil profile is assumed to be similar to that at the site) during the earthquake. Figure 3 shows a plot of movement of nearby survey benchmark levels.

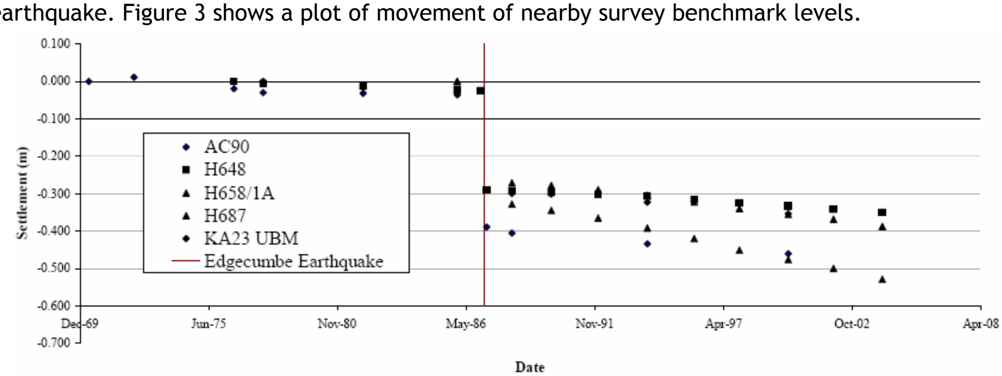

Figure 3: Plot of affected Benchmark Levels (Energy Surveys 2005)

Predicted ground surface settlements are summarised and compared with settlements observed following the earthquake in Table 4 below.

Table 4: Comparison of Predicted and Observed Settlements

Case	Observed following Edgecumbe Earthquake (0.3g)	Predicted (0.3g)
Survey Control	Average Settlement 290mm	50 – 150mm
Apprentice Training Centre (ATC)	Approximately 100mm	224 -270mm
Pipe Bridge	Approximately 350mm	50 – 150mm

The above indicates a significant variation with a ratio of between observed and predicted settlement of 37% to 230%. One possible reason for the apparent underprediction discrepancy in the survey control data is that the benchmarks provide an indication of absolute rather than differential settlement and may be affected by tectonic movement, another reason may be that at the pipe bridge the observed settlements may also result from deep seated lateral movement towards the nearby river. The apparent overprediction for the ATC may in part be that only obvious differential settlement delineated by an abrupt scarp was reported.

5 LATERAL SPREADING

During the Edgecumbe Earthquake, liquefaction induced lateral spreading affected areas up to 70m from the riverbank in the area of the Effluent Inflow Pipe and 55m from the riverbank at the Apprentice Training Centre, (BCHF 1987). Displacement at the Apprentice Training Centre was noted to be 50mm (lateral displacement) increasing to 350 mm near the riverbank. Lateral spreading analyses were therefore carried out to assess the potential for lateral spreading of the site and to form the basis of comparison with observed movement at the Apprentice Training Centre. Two methods of analysis have been used; these are detailed below.

5.1 Prediction of lateral spread displacements

Empirically derived displacements can be predicted using published correlations (Bartlett and Youd 1995, 2002) to geometric parameters. Assumptions are summarised below in Table 5.

Table 5: Empirical Lateral Spread Assessment

Parameter	ATC	Site (DBE)	Comment
Mw	6.5	6.5	Based on likely magnitude of movement on nearby faults with return periods likely to contribute significantly to the probabilistic seismic hazard (Stirling 2004)
R	15 km	10 - 15 km	Horizontal distance to earthquake source - two nearby active fault zones assessed as being likely sources for DBE level shaking.
Length	55m	150m	Distance to the river varies from 100m to 300m.
Height	10m	10m	Assumes Tarawera river 3-4m deep and bank 6-7m high.
Ground slope	0 deg	0 deg	Terrace assumed flat with spreading modelled as 'to free face'.
Predicted Displacement	0.5m	0.2 - 0.45m	The range in predicted movement of the Site results primarily from variation in the proximity to the fault and riverbank.

For the purpose of comparison, and to allow the evaluation of ground improvement measures, lateral spread displacements were also estimated by carrying out Newmark sliding block analyses using liquefied shear strengths derived from published correlations (Olsen and Stark, 2003). Analyses were carried out using limit equilibrium analysis adopting theoretical upper and lower bound liquefied shear strengths to confirm that FOS>1.0 for the liquefied static case and then to derive a range of yield acceleration values. The ratios of yield and peak seismic acceleration values were then used to derive the likely range of lateral spreading under the design event and to allow some quantitative evaluation of proposed foundation measures. Assumptions are summarised in Table 6.

Table 6: Semi Empirical Lateral Spread Assessment

Parameter	ATC	Site (DBE)	Comment
PGA (Scaled)	0.21	0.37g	Magnitude scaled peak ground acceleration for use with empirical displacement prediction methodology (Ambraseys and Menu 1988)
PGV		0.47m/s	Peak ground velocity for use with Cai and Bathurst (1996) displacement prediction methodology
Cu (Liq)	9kPa to 12kPa	2.2kPa/m @RL 21.2, 2.8kPa/m @RL 22.3	Range (Upper and Lower Bounds) of liquefied shear strengths based on Olsen and Stark methodology.
Kc	0.05g and 0.08g	0.04g and 0.08g	Range of yield accelerations (Upper and Lower Bounds)
Predicted Displacement	0.2 m to 0.4m	0.2m to 0.6m (0.2m to 0.4m)	Ambraseys and Menu 1988 and (Cai and Bathurst 1996)

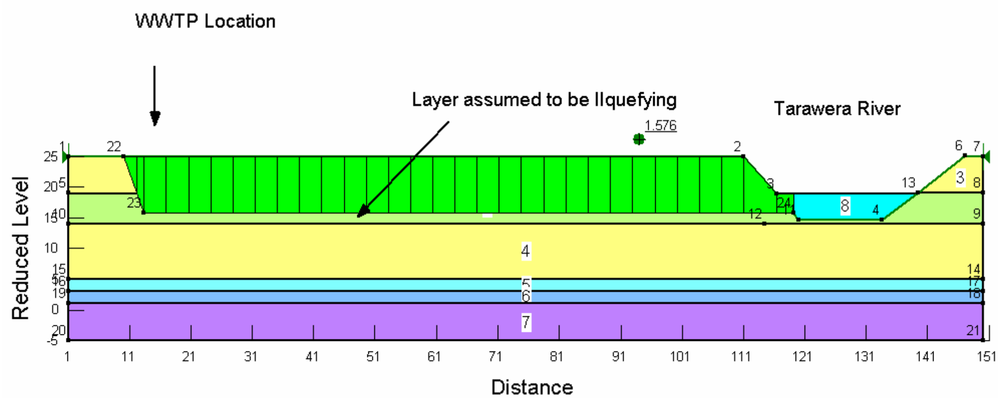

Figure 2: Site Section Analysed for Lateral Spread

5.2 Comparison of Predicted and Observed Lateral Spread

Predicted and observed displacements for two locations with soil profile information are compared in Table 7. The soil profile used for analysis of the ATC is based on machine borehole investigation carried out to investigate site stability following movement during the Edgecumbe Earthquake. The soil profile at the pipe bridge is assumed to be similar to the site (see Table 1).

Table 7: Comparison of Predicted and Observed Lateral Spreading

Case	Observed following Edgecumbe Earthquake	Predicted
Apprentice Training Centre	Approximately 50mm, 55m from riverbank, 300mm closer to riverbank.	200mm to 400mm (semi empirical) 500mm (empirical)
Pipe Bridge	Approximately 350mm	

This comparison indicates a variation ratio between observed and predicted of 57% to 167%, which is consistent with the 0.5x <Displacement< 2x envelope noted by Bartlett and Youd (1995).

6 CONCLUSIONS

The site is underlain by a considerable thickness of loose, young (<700 year old), low density cohesionless soils. Analyses indicate that under a significant seismic event the site is likely to be subject to liquefaction and associated effects potentially including settlement and lateral spreading. We sought to validate predicted behaviour by analysing a selection of locations in the vicinity of the site where liquefaction related effects were observed during the 1987 Mw 6.5 Edgecumbe Earthquake.

A significant variation was noted in and between observed and predicted ground surface settlement. There are considered to be number of possible reasons for this apparent discrepancy including tectonic movement affecting benchmark levels and the combined effect of settlement and lateral spread. The apparent overprediction for one of the sites may be that at the time only obvious differential settlement delineated by an abrupt scarp was reported.

Observed and predicted lateral spread compared favourably with the 0.5x <Displacement< 2x envelope noted by Bartlett and Youd (1995).

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