Application of the geotechnical step change provisions of the 2017 MBIE Guidelines for the Seismic Assessment of Buildings

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ABSTRACT

The Seismic Assessment of Existing Buildings, Technical Guidelines for Engineering Assessments ("the Guidelines") provides engineers with a consistent means to assess the seismic behaviour of existing buildings with respect to life safety. The expectation for a new building designed in accordance with current good practice is that it should be able to sustain in excess of 1.5-2 times the ULS displacement while still achieving its life-safety objectives. This same expectation is transferred to the assessment of existing buildings with ULS scaled to reflect the *%NBS* rating attained. To achieve this expectation in the evaluation of the effects of geotechnical aspects on existing building behaviour the Guidelines require that the behaviour of the soils under ever increasing levels of seismic shaking be considered. However, when this behaviour is expected to lead to a rapid deterioration in the soil resistance available (referred to as a step change), the capacity of the soil is required to be limited to half of either the deformation or the level of shaking at which the deterioration is estimated to occur.

Within the Guidelines, geotechnical Severe Structural Weakness provisions have prescriptive requirements for certain types of buildings, but the geotechnical step change provisions are open to interpretation, particularly when considering the impact on the supported structures. This paper will provide commentary on the intent and application of the geotechnical step change provisions and will present practical examples taken from real-world projects.

1 INTRODUCTION AND PURPOSE OF GUIDELINES

The Seismic Assessment of Existing Buildings, Technical Guidelines for Engineering Assessments (hereafter referred to as "the Guidelines") were published in July 2017 and subsequently updated in November 2018. The Guidelines were a joint effort between the New Zealand Society for Earthquake Engineering (NZSEE), the Structural Engineering Society of New Zealand (SESOC), the New Zealand Geotechnical Society (NZGS), the Earthquake Commission (EQC), and the Ministry of Business, Innovation, and Employment (MBIE). The Guidelines were prepared with significant input from across the earthquake engineering professional and academic community.

The purpose of the Guidelines is to provide engineers with a consistent means to assess existing buildings for seismic actions and to effectively and consistently communicate the results (§A1.3). The underlying principle of the assessment procedures is a focus on life safety as the primary objective (§A3.1). The consideration of life safety hazards includes both the structural capacity of the primary structure and also hazards posed by secondary and non-structural elements. By using the concept of *%NBS* (% new building standard as required by the Building Code as assessed using the Guidelines), the Guidelines assessment process seeks to provide a rating based on an acceptable level of performance across all levels of earthquake shaking, although the assessment procedures are based on comparing assessed (probable) capacity against the design level shaking/loads/displacements for new buildings (Ultimate Limit State [ULS] shaking). The concept of *%NBS* implies a margin to undesirable outcomes such as collapse, which is consistent with implicit margins for new designs completed to the Building Code, but to the levels of demand scaled by the *%NBS* rating.

A building's *%NBS* earthquake rating is determined by finding the lowest *%NBS* score of any element of the building. This element is then considered to represent the Critical Structural Weakness (CSW). An important aspect of the Guidelines is the focus on life safety, so a CSW requires a Significant Life Safety Hazard (SLSH) to develop if the element were to fail.

The score is the ratio between the probable capacity as determined by the Guidelines and the 100%ULS demand requirements. The probable capacity is as determined by the Guidelines or as inferred from design procedures but without the application of the strength reduction factor. There are two circumstances in the assessment of geotechnical aspects that require further consideration and adjustment. One is when a defined severe structural weakness (SSW) is present. (The Guidelines define two such geotechnical situations: complex slope failure resulting in potential loss of more than 50% of the building platform, and when liquefiable ground supports poorly tied together URM buildings.) The other is when step change behaviour is identified in the resistance provided by the foundation soils. Step change behaviour can also occur when the ground imposes demand on the structure. This latter case is not well addressed by the Guidelines. This paper discusses the application of the step change provisions and applies these to several examples that have been encountered by the authors.

2 GEOTECHNICAL STEP CHANGE AND DEFINITIONS

From the Guidelines, the relevant definitions related to the approach for determining geotechnical capacities (resistances) are:

Per §C4.5.3 of the Guidelines,

> *When a step change in behaviour is expected it will be necessary to estimate the deformation (or %ULS shaking) at which this is expected and also to consider the probable residual strength capacity that might be available beyond the step change. In line with the assessment philosophy that has generally been adopted in these guidelines around step change behaviours, the deformation (or %ULS shaking) at which the step change is indicated is divided by 2 when defining the model. Beyond this halved deformation, the resistance is*

> *assumed to be limited to the residual capacity. The objective is to determine a %NBS score which has the resilience that is likely to be inherent in current new building design.*

§C4.5.3.2 states that

> *geotechnical step change is only an issue for setting the earthquake rating if it in turn results in a step change in the behaviour of the building structure (a structural step change), and then only one that would result in a SLSH.*

Per §A3.1.1, a SLSH is defined as

> *An unavoidable danger that a number of people are exposed to. … Failure of a building or building section as a whole (leading to collapse) is considered to be a significant life safety hazard but failure of individual members/elements in the primary structure will only constitute a significant life safety hazard, when considered individually, if their failure causes them to fall. A significant life safety hazard can also result from the loss of gravity load support of a member/element of the secondary structure, or of the supporting ground, or of non-structural items that would reasonably affect a number of people.*

There are three important underlying principles embodied in these statements that form the philosophy behind the application of the geotechnical step change provisions.

The first principle is that the intent of the Guidelines is to provide ratings that reflect the expectation/need of ongoing performance well beyond ULS shaking, albeit not necessarily at the same level of reliability as required at ULS. This is to ensure that there is reasonable confidence the building can meet the holistic life safety performance objectives set out in clause B1 of the Building Code. In most structural applications, this reliability is already accounted for when using the Guideline procedures, as these procedures are linked reasonably closely to those used for the design of new building work where the same underlying philosophies also apply. Where they are not expected to be sufficient, the SSW structural provisions apply. Step changes in geotechnical conditions have also been identified in the Guidelines as an issue in this regard. If reliance is going to be placed on pre-step change probable capacity, then the Guidelines require that these capacities should not be assumed beyond one half of the deformation or the %ULS shaking level at which the step change is determined to occur. As an alternative, the post-step change probable capacity can be taken.

The second underlying principle is that a step change in the ground behaviour is only relevant as it affects the structural performance. A geotechnical step change that does not cause undesirable behaviour in the structure does not need to be reflected in the rating of a building.

The third underlying principle is that the probable capacity for the building should be based on the point at which a SLSH develops, which is not necessarily the first time any element in the building exceeds its probable capacity. For instance, in a concrete frame building, a single beam exceeding its probable capacity (hinging at both ends) would be unlikely to lead to the beam falling or, on its own, to the probable capacity of the building being reached. A full mechanism in the frame with many beams reaching their probable capacity would be required to attain this latter condition.

There is a further situation that can arise in the case of geotechnical conditions which is not well covered in the Guidelines, and that is when the behaviour of the soil places demands on, rather than supports, the structure, such as in a case where lateral spreading imposes deformation on a building. An approach for this can be inferred from these Guideline provisions and a possible approach is outlined in Section 3.3 below.

3 APPLICATION OF THE GEOTECHNICAL STEP CHANGE PROVISIONS

There are several types of nonlinear geotechnical behaviour. In this paper, we will examine three:

- Foundation elements exhibiting step change behaviours. These elements exhibit behaviour with a sharp drop-off in load-carrying capacity.
- Liquefaction or cyclic softening. After a certain “trigger point” of shaking, the ground has significantly reduced vertical and lateral load-carrying capacity.
- Ground deformation. As shaking increases, the ground deforms and imposes displacements on the structure. This type of behaviour includes slope instability, cyclic displacement, and lateral spread.

Note that some of these behaviours may occur in combination; however, we will be treating each case individually. We are presenting necessarily simplified data and examples for purposes of explaining principles. Engineering judgment must be applied in using the Guidelines and this commentary.

3.1 Foundation elements exhibiting step change behaviour

3.1.1 Assessment steps

Foundation elements exhibiting step change behaviours could include tension piles and anchors relying on shaft resistance in rock. These elements could exhibit behaviour with a large and sudden reduction in load-carrying capacity after reaching their peak. This reduction in capacity constitutes a geotechnical step change.

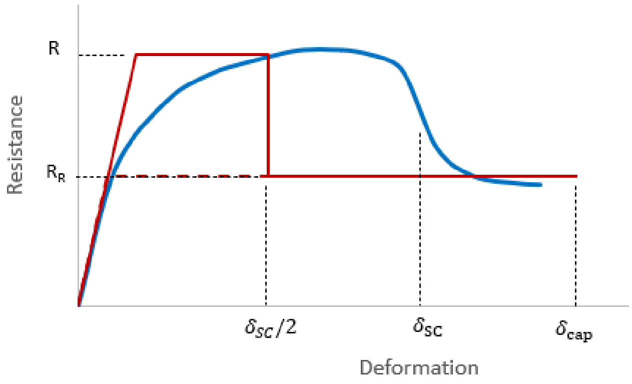
Load testing of foundations to displacements beyond that at which the ultimate geotechnical capacity is recorded is not common; consequently, there is limited data available on behaviour of these foundations at larger displacements, whether they exhibit step change behaviour, or at what displacement this is likely to occur.

In some existing buildings, step change behaviour in foundations may not have been mitigated against and it will be necessary to identify if this type of behaviour is possible. Most foundation types are not expected to exhibit step change behaviours to an extent that could be expected to affect earthquake ratings for existing buildings.

Figure 1 shows a schematic load-displacement behaviour plot of a foundation exhibiting step change behaviour. The blue line on this Figure is a best estimate of the “probable resistance” of the foundation. In reality, there will be uncertainty and a wide range of possible behaviour. This uncertainty has not been shown on the Figure for clarity. In developing the blue line, the critical parameters which the geotechnical engineer needs to identify include:

R: The probable ultimate geotechnical capacity
R_R: The probable residual geotechnical capacity after the step change
δ_{SC}: The probable displacement at which a step change in resistance could be expected.

The red line on the Figure is a simplification of the blue line for application to structural analysis. Note that in this simplified, modelled behaviour the displacement at which the step change occurs is halved. This is to provide some resilience against this unfavourable step change behaviour. Also note that as an alternative to the solid red line of modelled behaviour the dashed red line may be applied in structural analysis and assessment, i.e. assuming the residual capacity from the beginning. It is valuable to start the assessment by making a best estimate of the profile of the blue line – the probable resistance. This helps to identify if a step change exists: a sudden and large reduction in capacity. It also helps in understanding the simplifications represented by the red line (and the dashed red line).



Legend

—	Expected/probable foundation capacity
—	Assumed expected/probable foundation capacity
- -	Assumed expected/probable foundation capacity relying only on residual capacity
R	Probable ultimate geotechnical capacity
R_R	Probable residual geotechnical capacity after the step change
δ_{SC}	Probable displacement at which a step change in resistance could be expected
$\delta_{SC}/2$	Half of δ_{SC}
δ_{cap}	Assumed geotechnical probable deformation capacity limit. Beyond this deformation R_R cannot be relied on.
δ_{SLSH}	Displacement at the onset of a Signficant Life Safety Hazard
x_{SC}	Probable % ULS shaking at which step change (liquefaction) in resistance (capacity) could be expected.
$x_{SC}/2$	Half of x_{SC}
G	%ULS shaking corresponding to onset of ground deformation
Y	%ULS shaking corresponding to δ_{SLSH}
2X	%ULS shaking corresponding to $2\delta_{SLSH}$
X	Half of 2X

Figure 1: Foundation element exhibiting step change behaviour, and legend for all figures in paper

In this case, the following steps should be taken to assess the impact of the geotechnical step change.

1. The geotechnical engineer should identify whether a geotechnical step change in the resistance of the foundation element could occur. The structural engineer should identify if step change of this element could lead to a SLSH for the building. This initial assessment may be qualitative. To aid this assessment and communication we suggest that a sketch in the form of Figure 1 be prepared, including an initial estimate of the profile of the blue line.
2. If it is concluded that a geotechnical step change could be expected and that that step change could lead to a SLSH, the geotechnical engineer should evaluate the ultimate and residual capacities and the displacement at which the step change between these capacities could be expected. These should be reported in the form of Figure 1.
3. The structural engineer carries out a structural analysis of the system assuming the modelled geotechnical behaviour (the red line on Figure 1), using the elastic or nonlinear analysis processes, as appropriate, as outlined in the Guidelines. The structural engineer determines the relationship between the demands on the foundation element (resistance required or displacement imposed) and %ULS load on the system. The structural engineer also determines the displacement that can be tolerated before a SLSH develops in the structural system. The structural and geotechnical engineers discuss the conclusions of the structural analysis. This feedback loop is important because it allows a check on the application of the geotechnical parameters considering the impact on the structure.

4. The score for the element is the ratio of the %ULS shaking at which its modelled capacity is exceeded (either resistance or displacement) and 100%ULS demand. If the foundation element is considered to remain in the elastic range and below the assumed displacement capacity of the step change, the score is simply the ratio of the assumed probable geotechnical capacity and the demand at 100%ULS. If the critical SLSH displacement in the system is reached at a lower level of shaking, then that would govern over that determined for the foundation element.

Explicit consideration of the nonlinear behaviour of the foundation element (in this case being the nonlinear behaviour of the soil) could lead to a higher score than a simplified elastic analysis, but the extent of the increase will be significantly affected by step change behaviours. Consideration of nonlinear behaviour will generally require significant interaction between the geotechnical and structural engineers.

3.1.2 Example

In this example, we will consider the behaviour of a micropile grouted into rock loaded in tension.

1. The geotechnical engineer advises that a step change in the resistance is possible for the micropile. The structural engineer determines that the failure of the micropile in tension could lead to uplift in the frame above, which causes beam and column hinging in the adjacent frames. This beam and column hinging has the potential to create a mechanism that causes a floor collapse, which would be a SLSH.
2. Therefore, the geotechnical engineer provides a load-displacement behaviour plot shown in Figure 2 for use by the structural engineer.
3. The structural engineer first considers limiting the behaviour of the micropile to the elastic range. The structural engineer analyses the system utilising the initial micropile stiffness provided in Figure 2 and determines that the tension demand on the micropile at 100%ULS shaking is 1200 kN. The score for the micropile is (1000/1200)*%NBS* or 85*%NBS*. If likely to be significant, a range of initial stiffnesses may need to be considered.
4. The structural engineer could consider allowing the micropile to exhibit nonlinear behaviour as shown in Figure 2. The structural engineer would check that the load can be sustained in the micropile and structural system and then analyse the system incorporating the nonlinear behaviour of the micropile (both tension and compression). For displacements in the micropile up to 20 mm a probable capacity of 1000 kN can be assumed, beyond which the capacity must be assumed to drop to 600 kN. The score for the system incorporating the nonlinear micropile can be calculated using the methods outlined in the Guidelines but may be limited by the capacity of the micropile. If a 600 kN micropile capacity provides sufficient resistance, the analyses could be simplified by assuming elasto-plastic behaviour at a probable load resistance of 600 kN.
5. A SLSH will result if the probable capacity of the micropile is exceeded and if the displacements in the structural system (including the displacements in the micropile) could lead to a failure in the system that meets the requirements of a SLSH as defined in the Guidelines.

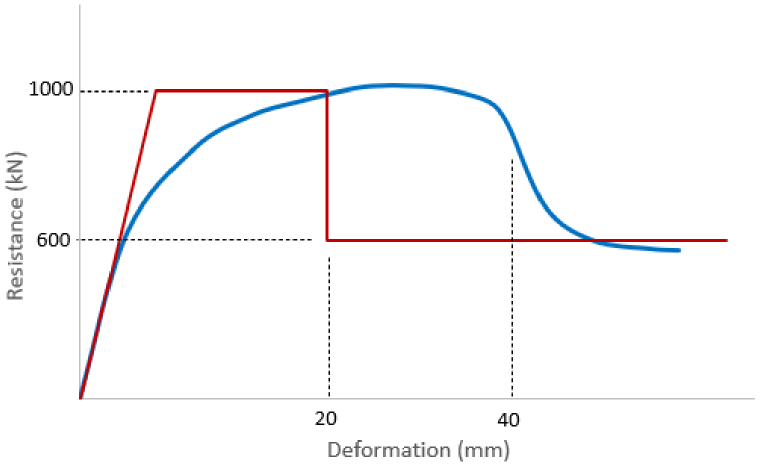


Figure 2: Micropile grouted into rock tension capacity example

3.2 Step change due to liquefaction

3.2.1 Assessment steps

After a certain "trigger point" of shaking, liquefaction of the soil can result in the loss of vertical and lateral load-carrying capacity of the foundation. This reduction constitutes a geotechnical step change. For shallow foundations, both the vertical and lateral load-carrying capacities are likely to be affected by liquefaction. For deep foundations, it is likely that vertical load-carrying capacity will be less affected by liquefaction; however the lateral load-carrying capacity is likely to be significantly decreased after liquefaction, depending on the depth of embedment and depth of the liquefiable layer(s). In most cases, a degradation of lateral load-carrying ability would not create a SLSH; however this would need to be confirmed for individual buildings.

As part of assessment of an existing building, any potential for liquefaction compromising the support of foundations and importantly whether that could lead to a SLSH needs to be identified. Punching failures of foundations were observed as a consequence of the Canterbury earthquake sequence, but these did not lead to collapse of those particular buildings.

Figure 3 shows a schematic relationship between foundation capacity (resistance) and intensity of shaking (%ULS shaking). Figure 4 shows schematic load-displacement plots for foundations with and without liquefaction effects; i.e. where liquefaction is not expected or the intensity of shaking is less than the trigger, and where liquefaction is triggered.

The commentary and legend for Figure 1 also apply for Figure 3 and Figure 4, i.e. the blue line is an estimate of probable resistance. The uncertainty and wide range of possible behaviours have not been shown on the Figures for clarity. In assessing the displacement with liquefaction (Figure 4) the geotechnical engineer is to include all mechanisms causing displacement with liquefaction during the shaking, including volumetric strain, sand ejecta and load-related displacements. Consequently, some displacement could occur without load as indicated on Figure 4. Note that if it is assessed that volumetric strain and ejecta could be expected to occur post-earthquake shaking at the particular site there would be justification in excluding these displacements.

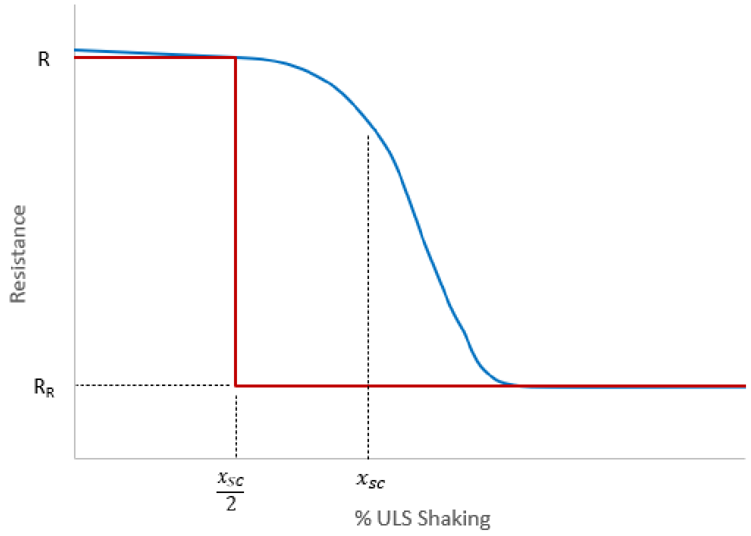


Figure 3: Resistance versus % ULS shaking for liquefaction scenario (adapted from Figure C4-3(b) of the Guidelines)

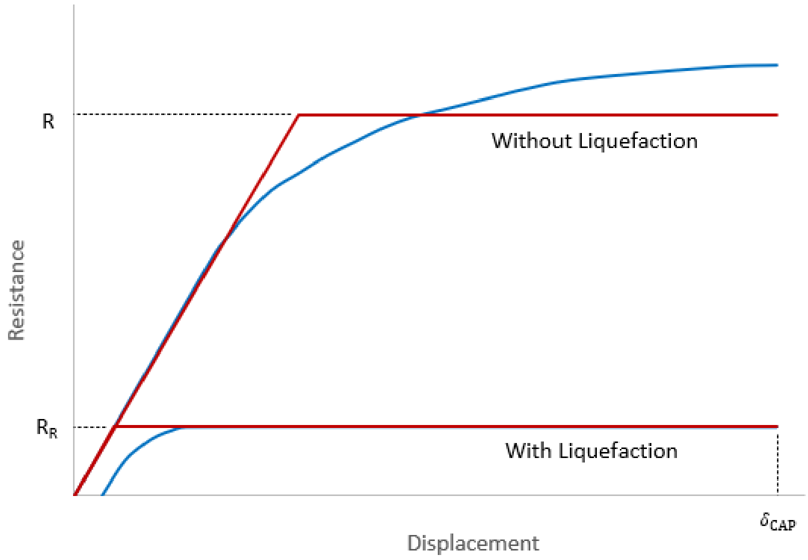


Figure 4: Resistance versus displacement for liquefaction scenario

In this case, the following steps should be taken to assess the impact of the geotechnical step change.

1. Initially the geotechnical and structural engineers jointly complete a qualitative, and possibly limited quantitative assessment of the likelihood of liquefaction and of this causing a SLSH. If liquefaction and a SLSH are considered possible, the further steps of assessment below are followed.
2. The geotechnical engineer quantitatively assesses the potential for liquefaction and its impact on foundation behaviour. The conclusions are communicated to the structural engineer via sketches in the form of Figure 3 and Figure 4. Values of %ULS shaking for the assessed step change (triggering of meaningful liquefaction) and of the foundation capacity with and without liquefaction effects are provided. The geotechnical and structural engineer discuss and agree scenarios to be tested in the structural assessment. Developing these scenarios should consider if the liquefaction could be localised or widespread, and if localised, the vulnerability of the structure in the event of liquefaction affecting particular foundations. Possible unfavourable cases of localised liquefaction should be considered; i.e.

specific foundations having residual capacity (liquefaction effects) and other foundations having full capacity (no liquefaction effects).

3. The structural engineer assesses if any of these scenarios could lead to a SLSH for the building. This includes considering the ability of the structure to redistribute loads and tolerate the associated deformations as a consequence of the reduced foundation support. Figure 4 is to provide simplified foundation parameters as input to the soil structure interaction analysis.
4. If step 3 concludes that the reduced foundation support (R_R) and associated deformations could lead a SLSH in the structure, then the score for the liquefaction scenario is taken as $x_{sc}/2$.

3.2.2 Example

In this example, we will consider the vertical load-carrying capacity of a shallow pad footing on liquefiable soils.

1. Initially the geotechnical and structural engineers jointly determine that liquefaction is possible on the site, and that a reduction in bearing capacity at the footing could result in large vertical displacements, which could create beam and column hinging in the frame structure. This beam and column hinging has the potential to create a mechanism that causes the floor to fall, which would be a SLSH.
2. The geotechnical engineer provides a capacity-shaking behaviour plot shown in Figure 5 and Figure 6 for use by the structural engineer. The geotechnical engineer advises that the step change is assessed by judgment to occur at 40% ULS shaking.
3. The structural engineer determines that if liquefaction does not occur the bearing pressure demand on the footing is 250 kPa at 100%ULS with a resulting displacement of 65 mm (refer Figure 6), which for the purposes of this example is assumed can be sustained by the structure. Without liquefaction, the score would therefore be 100*%NBS*. The structural engineer confirms that in the event of liquefaction a SLSH in the structure could be expected. Therefore, allowing for liquefaction, the score for the foundation is taken as the higher of 40%/2 = 20*%NBS* considering step change behaviour or 25*%NBS* (60/250) if the capacity after liquefaction is assumed. The score is 25*%NBS*.

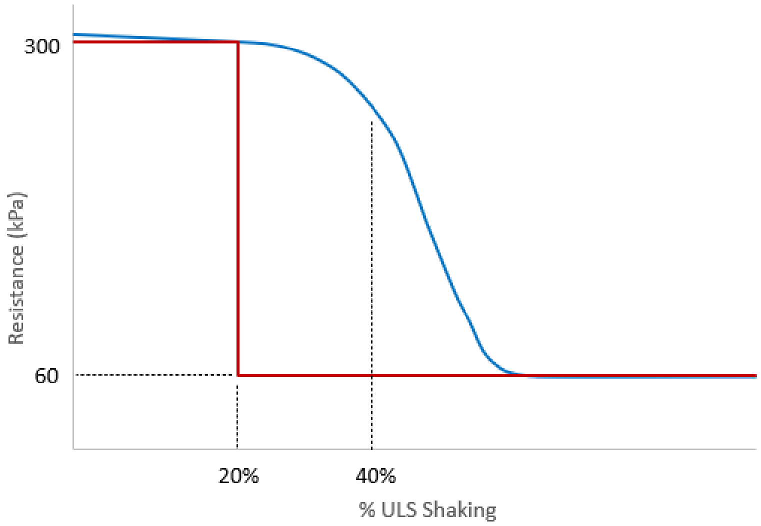


Figure 5: Bearing capacity of a shallow foundation example

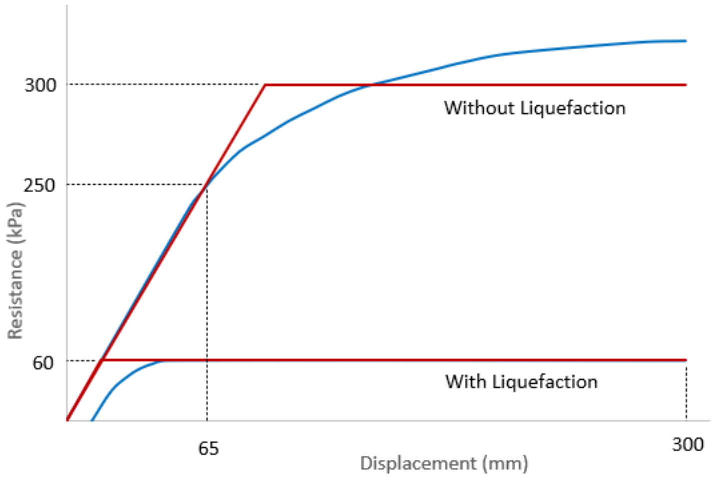


Figure 6: Bearing capacity versus displacement of a shallow foundation example

3.3 Step change due to ground deformation

3.3.1 Assessment steps

The two previous cases are explicitly covered by the Guidelines in §C4.5.3. The case of ground deformation leading to demands on the structural system is not explicitly discussed. The assessment approach laid out below is based on applying the same underlying philosophy as the previous two cases.

As shaking increases, the ground deforms and imposes displacements on the structure above. This type of behaviour includes slope instability, cyclic displacement, and lateral spread. Figure 7 shows a schematic displacement-shaking behaviour plot. The legend presented in Figure 1 relates to Figure 7. δ_{SLSH} is the displacement at the onset of a Significant Life Safety Hazard. Y is the %ULS shaking causing this displacement and 2X is the %ULS shaking causing double this displacement. X is half of 2X. G is the %ULS shaking at the onset of ground deformation.

If the displacement-shaking behaviour indicates a sudden increase in deformation with shaking, this could represent a geotechnical step change as defined by the Guidelines. In the case of slope instability, a steep slope is more likely to have a sudden increase in displacement than a gentle slope. In the case of lateral spread, a sudden increase in displacement with shaking is more likely at locations close to the free edge than locations more distant.

The following steps are proposed to assess if a geotechnical step change could occur and how to account for that step change in the assessment.

1. Initially the geotechnical and structural engineers jointly complete a qualitative, and possibly limited quantitative assessment of the likelihood of ground deformation and of this causing a SLSH. If ground deformation and a SLSH are considered possible, the further steps of assessment are followed. These steps include assessing if the ground deformation could represent a geotechnical step change as defined by the guidelines and application of the geotechnical step change provisions if appropriate. The structural and geotechnical engineers discuss and agree ground deformation scenarios to be tested in the structural assessment. A scenario could be differential displacement between two parts of the structure leading to a SLSH.
2. The structural engineer undertakes structural assessment of the agreed scenarios and determines the imposed displacement that would cause a SLSH, referred to as δ_{SLSH}.
3. The geotechnical engineer undertakes quantitative assessments and models the displacement-shaking behaviour for the agreed scenarios. The geotechnical engineer communicates the conclusions to the

structural engineer via plan and cross-sectional sketches plus plots of displacement-shaking behaviour in the form of Figure 7, including the point at which lateral spread is expected to initiate (G), the point identified by the structural engineer as creating a SLSH (δ_{SLSH}), and the point corresponding to twice δ_{SLSH}. Displacement-shaking behaviour plots at different locations across the site may be required.

4. Refer Figure 7. The structural engineer and geotechnical engineer should review the slope of the line between points G and δ_{SLSH} (noted as K_1) against the slope of the line between δ_{SLSH} and 2 δ_{SLSH} (noted as K_2).
    a. If the slope $K_1 \geq K_2$, this shows that the displacement is increasing beyond Y at a decreasing rate. This can be tolerated. An unfavourable and sudden increase in displacement is not indicated. A step change is not identified. The assessed score would be the %ULS shaking causing δ_{SLSH}, Y*%NBS* in Figure 7. Care and engineering judgment need to be applied in making this assessment. If it is judged that because of uncertainty $K_1 < K_2$ is possible and the consequences of larger displacements are severe for the structure, it may be appropriate to assume a step change as described in b below.
    b. If the slope $K_1 < K_2$, this indicates that the displacement is increasing beyond Y at an increasing and potentially uncertain rate. This is not tolerable nor consistent with the objectives of reasonably predictable behaviour at levels of shaking beyond that of the earthquake score. The score in this situation is proposed to be the shaking corresponding to 2x δ_{SLSH} divided by 2, X*%NBS* in Figure 7. This methodology maintains a margin of 2 for both %ULS shaking and displacement in a nonlinear environment.
    c. The above procedure differs from that in the Guidelines for foundations with step change behaviours and liquefaction because for those situations, the intent is to reduce the assumed available capacity to a level that allows the risk of reaching the step change to be acceptable.

The authors have proposed the above procedure as a method of testing for step change and to illustrate the philosophy to be applied. That philosophy is that if deformation increases with intensity of earthquake shaking at a faster rate beyond δ_{SLSH} than it did before δ_{SLSH} then step change provisions should be applied. The philosophy is also to maintain a margin of at least 2 to both the δ_{SLSH} and the %ULS shaking in the case where a step change is identified. The procedure requires identifying the intensity of earthquake shaking (%ULS shaking) at the onset of deformation (G) and at δ_{SLSH} and 2x δ_{SLSH}. Identifying these values includes considerable uncertainty and requires judgement. The important thing is to keep in mind the intended overall philosophy. Alternatively, a simplification of the procedure is for the geotechnical engineer to identify a %ULS shaking at which an increase in lateral deformation occurs (a geotechnical step change) and the associated total deformation. If this deformation results in a SLSH then the score for this deformation and SLSH relates to the %ULS shaking of the step change reduced by a factor of 2. This simplified assessment may be refined by the procedure outlined by steps 1 to 4 described above if considered necessary.

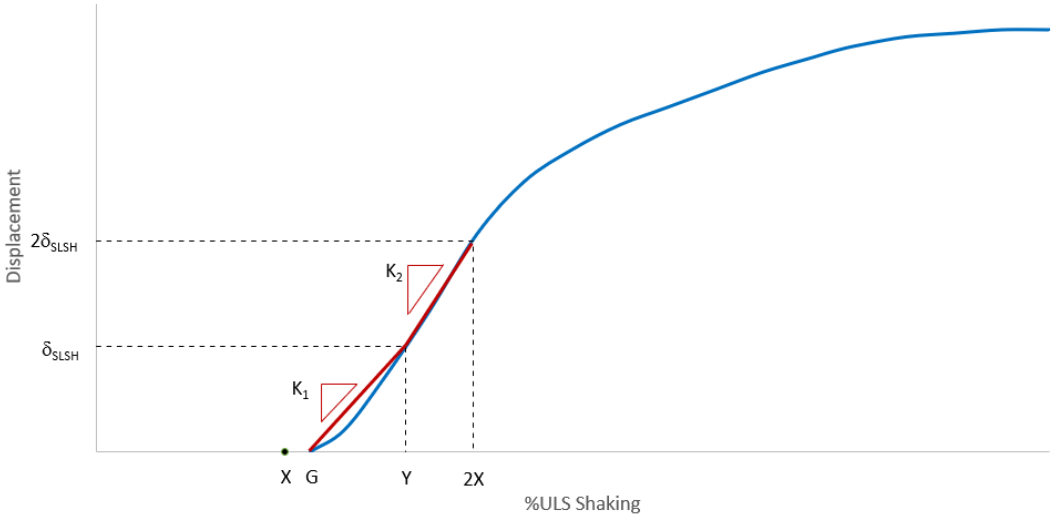


Figure 7: Displacement vs shaking in ground deformation scenario

3.3.2 Example

In this example, we will consider a staircase supported on a ledge. The ledge is supported by columns that can move independently of the base of the staircase in a lateral spread event. This example is taken from a real-world project. See Figure 8 for a schematic diagram.

1. The geotechnical engineer advises that lateral spread is possible on the site. The structural engineer determines that lateral spread causing separation between the columns supporting the ledge and the base of the stairs could cause the stairs to fall off their support, causing a SLSH.
2. The structural engineer determines that a displacement of 150 mm will cause the stairs to fall off the ledge. Because this is a binary outcome (either they are on the ledge or off it), the structural engineer divides 150 mm by 2 to determine an acceptable displacement, 75 mm, which is the probable capacity of the stair-ledge element. This is consistent with §8.8.3 of NZS1170.5.
3. The geotechnical engineer provides a displacement-shaking plot shown in Figure 9 for use by the structural engineer. This plot is for the agreed scenario of differential displacement between the columns supporting the ledge and the base of the stairs. The plot shows an S-shaped behaviour, which is nonlinear. The values at the critical points are determined as shown.
4. Using Figure 9, the structural engineer determines that the slope of the first line is (75 mm – 0 mm) / (40% - 25%) = 5 mm/%. The structural engineer then determines that the slope of the second line (150 mm – 75 mm) / (90% - 40%) = 1.5 mm/%. The units are not important as long as they are consistent.
    a. K_2 is less than K_1, therefore there is not a heightened risk of the stair falling off the ledge with increasing shaking. Therefore, the score is 40%*NBS* (the available capacity of 75 mm is reached at 40%ULS shaking).
5. Alternatively, instead of providing the detailed information outlined in Figure 9, the geotechnical engineer advises that a step change of lateral spread is expected at 35%ULS shaking and the magnitude of the lateral spread after that step change is expected to be 50mm. The structural engineer assesses that this deformation can be tolerated by the structure (50mm<75mm) and therefore step change provisions need not be applied. Further geotechnical assessment would then be required to evaluate the %ULS shaking causing the 75mm deformation to be applied to the scoring. If this score is important to the assessment further assessment as described in 4 above could be applied.

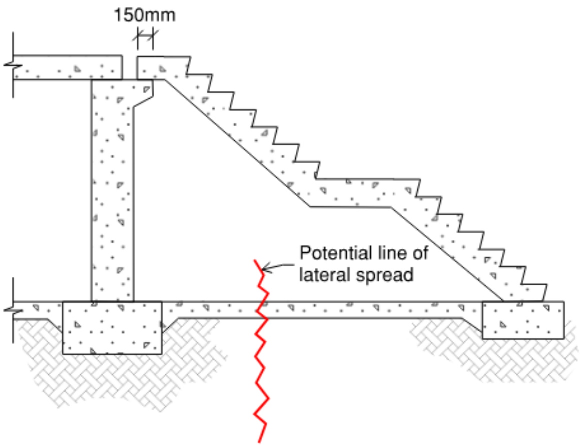


Figure 8: Schematic diagram for stair example

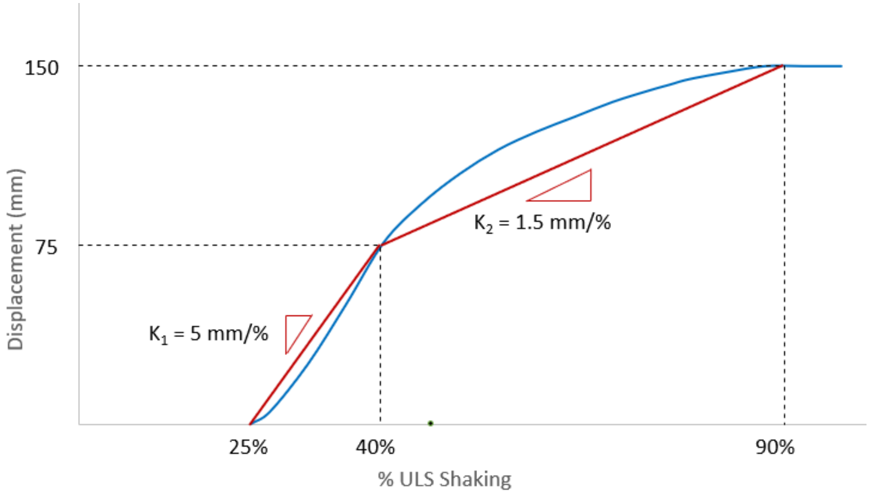


Figure 9: Displacement versus shaking for stair example

3.3.3 Example

In this example, we will consider a column in a frame supporting precast flooring. The columns of the frame are not well tied together at their base and can move independently if lateral spread develops between them. This example is taken from a real-world project. See Figure 10 for a schematic diagram.

1. The geotechnical engineer advises that lateral spread is possible on the site. The structural engineer determines that lateral spread causing separation between the column foundations could shear off piles supporting the columns, causing a vertical settlement and rotation of the beams supporting the precast flooring, causing a SLSH.
2. The structural and geotechnical engineers determine that the ground displacement consistent with reaching the probable shear capacity in the pile to be 150 mm. Pile shear could lead to the SLSH described.
3. The geotechnical engineer provides a displacement-shaking plot shown in Figure 11 for use by the structural engineer. The plot shows nonlinear behaviour.
4. Using Figure 11, the structural engineer determines that the slope of the first line (150 mm – 0 mm) / (40% - 20%) = 7.5 mm/%. The structural engineer then determines that the slope of the second line (300 mm – 150mm) / (55% - 40%) = 10 mm/%. The units are not important as long as they are consistent.

a. K_2 is greater than K_1, therefore there is an undesirable increase in the rate of demand with increasing shaking.
b. The score is the shaking corresponding to 2 x δ_{SLSH} (2 x 150 mm) divided by 2, which is 55%/2 = 30*%NBS*. (Scores are rounded to avoid providing the appearance of more precision than is warranted by the assessment methods.) This ensures the reported score has a margin of 2 in both the shaking and displacement.

5. Alternatively, instead of providing the detailed information outlined in Figure 11 the geotechnical engineer advises that a step change of lateral spread is expected at 40%ULS shaking and the magnitude of that lateral spread is expected to be >150mm. The structural engineer assesses that this deformation cannot be tolerated by the structure and therefore step change provisions need to be applied; namely 40%/2=20%NBS. If this score is important to the assessment further assessment as described in 4 above could be applied.

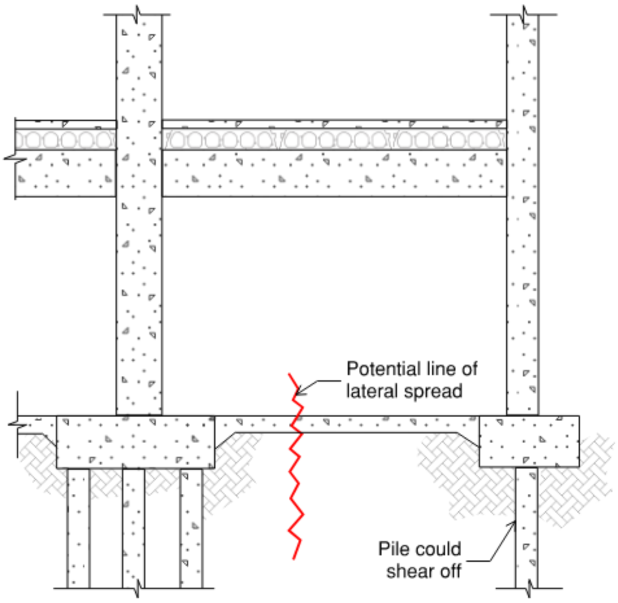


Figure 10: Schematic diagram for pile shear example

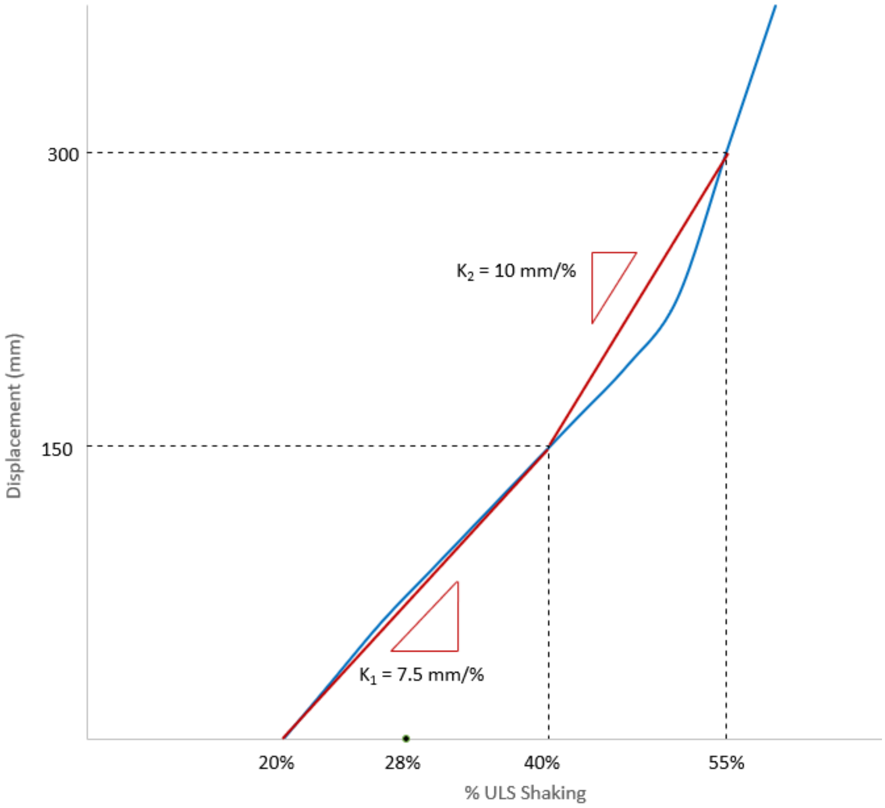


Figure 11: Displacement versus shaking for pile shear example

4 CONCLUSIONS

All three types of geotechnical behaviour discussed in this paper have step changes. The philosophy behind assessing the structural score for each is consistent, namely:

- The geotechnical step change has to impact the structure.
- The impact on the structure has to cause a SLSH.
- The score has to reflect a margin to undesirable behaviour and to reflect the inherent uncertainties.

While the steps to assessing the structure subjected to different types of geotechnical step change behaviours are different for each case, the underlying principles are consistent, and are in keeping with the philosophy outlined in the Guidelines for assessing buildings from a life safety perspective.

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REFERENCES

Ministry of Business, Innovation and Employment. 2019. The New Zealand Building Code Clause B1 Structure, incl Amendment 19.

Ministry of Business, Innovation and Employment. 2017. The Seismic Assessment of Existing Buildings, Technical Guidelines for Engineering Assessments.

Standards New Zealand. 2016. Structural Design Action - Part 5: Earthquake Actions NZS1170.5.