Geotechnical challenges for a mixed-use development at Gibsons, BC

Karim Karimzadegan, M.A.Sc., P.Eng.
Principal, Horizon Engineering Inc., North Vancouver, BC.

Nima Tafazzoli, Ph.D., P.Eng.
Geotechnical Engineer, Horizon Engineering Inc., North Vancouver, BC.

Takahiro Shozen, M.A.Sc., P.Eng.
Geotechnical Engineer, Horizon Engineering Inc., North Vancouver, BC.

ABSTRACT The subject site is located on the waterfront in the town of Gibsons, BC. The proposed development comprises a multi-level hotel, conference centre, and residential development, to be partially supported over two to three parkade levels, and offshore amenities. The Town of Gibsons and the subject site are underlain by the Gibsons Aquifer. Several phases of subsurface investigations were carried out at the subject site. Potential geotechnical challenges for this project were recognized as artesian groundwater pressures, high non-artesian groundwater levels, loose and compressible soil, and liquefaction. Seepage, deformation, and slope stability analyses were carried out to assess the site and subsurface conditions during and after construction of the proposed development. Due to the presence of loose and compressible subgrade materials, and artesian groundwater pressures, ground improvement in a form of Deep Mixing (DM) beneath the proposed foundations was recommended.

Site Description and Proposed Development

The subject site is located on the waterfront in the town of Gibsons, BC, as shown on Fig. 1. The site is bounded by Gower Point Road to the west, Gibsons Harbour (Howe Sound) and existing docks to the east, an adjacent residential property to the south, and an adjacent park to the north. The proposed development comprises a multi-level hotel, conference centre, and residential development, to be partially supported over two to three parkade levels, and offshore amenities.

Topography in the vicinity of and within the site is generally sloping gently down to the southeast toward the ocean, though a moderately steep slope exists at the northwest portion of the site.

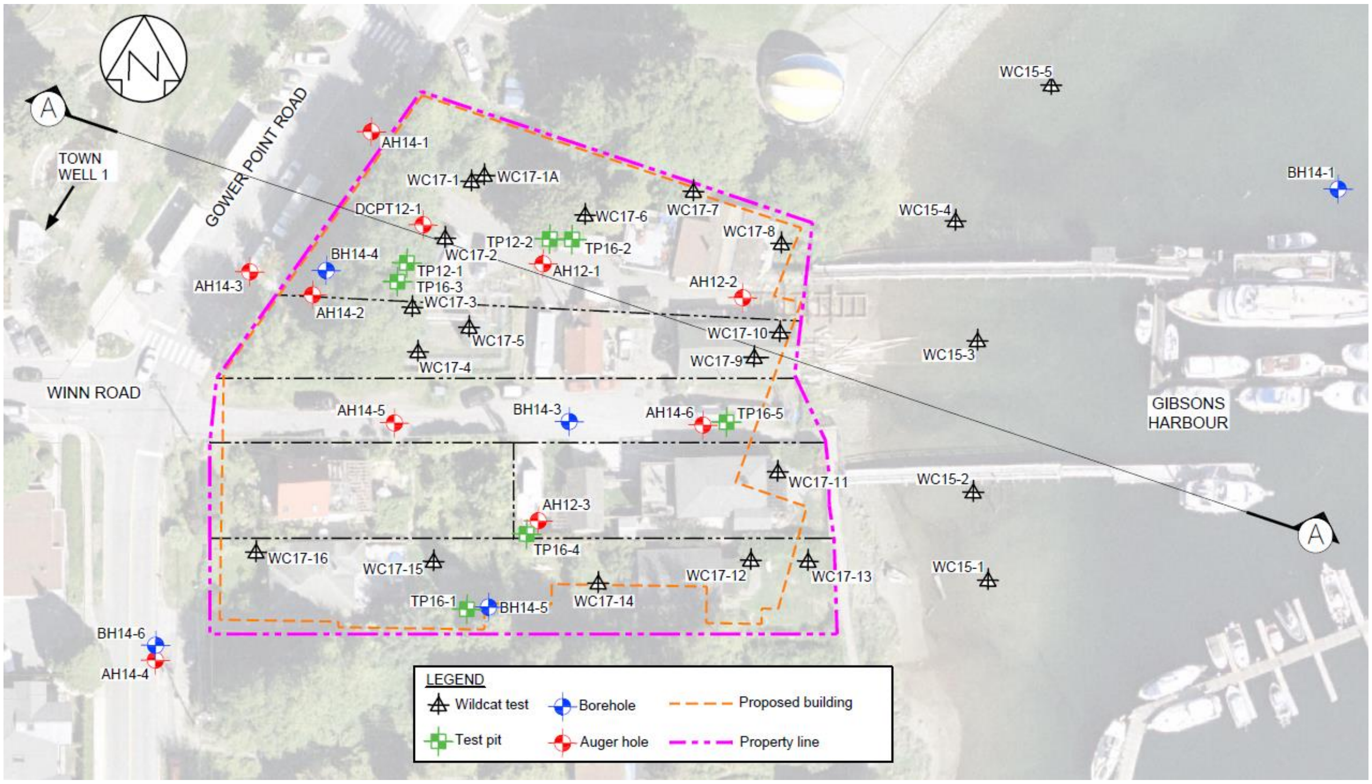
Geology and Hydrogeology

The Town of Gibsons is underlain by the Gibsons Aquifer, which is a confined aquifer comprising sand and gravel that provides drinking water for the town. An Aquifer Mapping study was carried out by Waterline Resources Inc. (2013). Doyle (2013) also carried out groundwater flow modelling to investigate the groundwater sustainability in Gibsons, BC.

A significant portion of the recharge to the Gibsons Aquifer occurs via mountain block recharge on Mount Elphinstone (located northwest of the town) or recharge through creekbeds in the aquifer catchment area. Over most of its areal extent, the Gibsons Aquifer is confined by low hydraulic conductivity, till-like soils that are collectively termed the Gibsons Aquitard. In general, an aquitard is a low permeable material, specifically, a material that is significantly lower in permeability than the aquifer. At the subject site, the specific geological deposits termed the “Gibsons Aquitard” includes a number of sedimentary deposits that have different geotechnical properties. The confining Gibsons Aquitard is inferred to comprise variable thicknesses of sand, peat, silty sand to sandy silt to silt, and localized till-like materials within the subject site. In some areas, the Gibsons Aquitard is overlain by the unconfined alluvial deposits of the shallower Capilano Aquifer. The Gibsons Aquitard is generally thicker in the Upper Gibsons area than at the subject site. Its thickness diminishes substantially near the harbour. Artesian groundwater pressures have been observed within the Gibsons Aquifer.

The Gibsons Aquifer is understood to naturally discharge to the seabed beneath Gibsons Harbour. Hydraulic connections have been observed between the Gibsons Aquifer and the ocean at the central portion of the site and between the Gibsons Aquifer and the Town Well #1, located at the west of the subject site. It is required that the Gibsons Aquifer not be negatively impacted by the

Fig. 1. Location of the site and test holes



proposed development as it is the source of drinking water for the town.

Subsurface Investigation

Several stages of subsurface investigation were carried out at the subject site comprising drilling onshore and offshore auger and sonic holes, advancing Dynamic Cone Penetration Tests (DCPT) and WildCat Cone Penetration tests, excavation of test pits, and installation of piezometers to monitor the groundwater level and measure the head pressures in the aquifer. The approximate locations of the test holes are shown on Fig. 1. The purpose of the subsurface investigations was to characterize the aquitard and aquifer soil materials, depth to the top of the aquitard, the aquitard thickness, and measuring the artesian groundwater pressures within the underlying aquifer at the test hole locations.

Subsurface Soil and Groundwater Conditions

The soil stratigraphy encountered during the subsurface investigations is described as following.

• Fill: very loose to dense, sand with trace gravel to gravelly, no silt to trace silt, and trace debris and organics at some test hole locations at the northwest portion of the site;

• Peat: very loose to loose / very soft to stiff, fine grained sand to silt, mostly organic. The peat horizon is inferred to represent the natural ground surface prior to placement of overlying fill materials;

• Sand: loose to dense, trace to some gravel, and no silt to trace silt;

• Silty Sand to Sandy Silt to Silt: trace to some gravel;

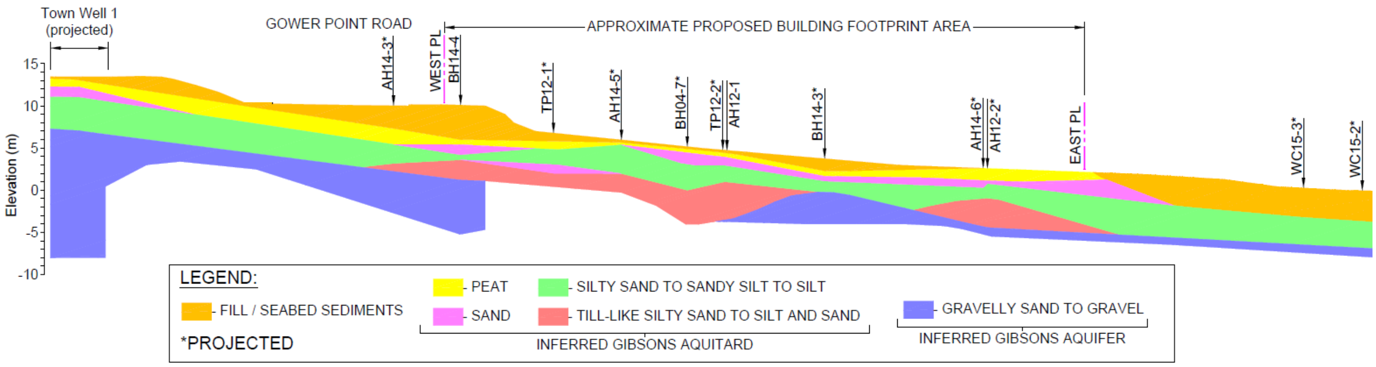
• Till-Like Silty Sand to Silt and Sand: very loose to very dense / soft to very stiff, no gravel to some gravel;

• Gravelly Sand to Sand and Gravel to Gravel: compact to very dense, occasional cobbles. These soil materials are inferred to comprise the Gibsons Aquifer.

A geotechnical section through the subject site along the west-east direction, including the general material types as described above, is shown on Fig. 2.

During the subsurface investigations, non-artesian groundwater was encountered at depths ranging from 0.9 to 3.7 metres at the locations of the test holes. Perched groundwater was also observed within the surficial fill materials at the test pit locations. The artesian groundwater pressures ranging from 12 to 41 kPa were measured at the locations of the piezometers installed into the aquifer during the months of December 2014 and January 2015. The hydraulic heads observed at the locations of these piezometers, along with the tidal elevations and average

Fig. 2. Geotechnical section A-A through the subject site along the west-east direction



daily pumping rates for the nearby Town Well #1, are shown on Fig. 3.

It is noteworthy that a direct correlation between the measured hydraulic head and the tidal elevations in Howe Sound is evident at the location of BH14-5 (approximately 60 metres from the harbour), which indicated a strong hydraulic connection between the Gibsons Aquifer and the ocean. At the location of BH14-6, the correlation between tidal elevations and measured hydraulic head is muted relative to that observed at BH14-5 (approximately 120 metres from the harbour), presumably due to the greater distance to the shoreline and greater vertical separation between the harbour and the top of the Gibsons Aquifer. At the location of BH14-4 (located approximately 75 metres from the harbour), the correlation between tidal elevations and measured hydraulic head is further muted relative to BH14-6, presumably due to the greater vertical separation between the harbour and the top of the Gibsons Aquifer. Although tidal effects can be seen at the location of BH14-4, the more pronounced time series signature at this location is a sharp decline in hydraulic head that occurs approximately every 34 hours. This head drop appears to be due to the periodic pumping of Town Well #1, which is located approximately 45 metres from BH14-4.

Potential Geotechnical Challenges

Some of the geotechnical challenges for this project were recognized as artesian groundwater pressures, high non-artesian groundwater levels, loose and compressible soil, and liquefaction.

Artesian Groundwater Pressures

The potential challenges with respect to artesian groundwater pressures could be ground heave of the aquitard materials following excavation of overlying soils, potential breach in aquifer, puncturing the aquifer with deep foundations, formation of an uncontrolled sinkhole, depressurization of the aquifer, ground settlement following depressurization, and contamination of the aquifer, which is a drinking water source for Gibsons.

High Non-Artesian Groundwater Levels

Non-artesian groundwater was encountered during the subsurface investigations at depths ranging from 0.9 to 3.7 metres at the locations of the test pits and auger holes. Most of these groundwater levels are higher than the proposed excavation elevation at the northwest portion of the site. Therefore, significant groundwater is expected to be daylighted during excavation at the northwest portion of the site. Potential geotechnical challenges associated with high non-artesian water levels would include temporary construction dewatering, permanent foundation drainage or waterproofing of the structure.

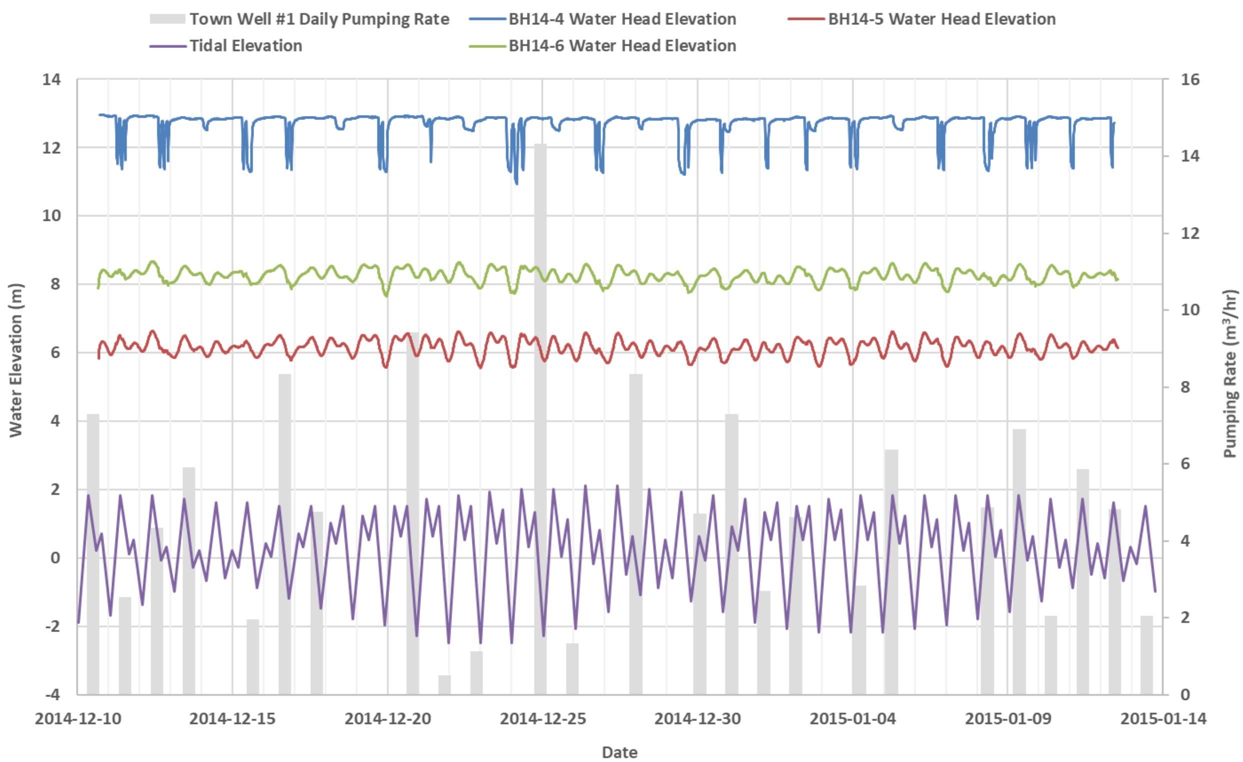
Loose and Compressible Soil

Significant thicknesses of loose and compressible soils were encountered at the test hole locations. If these soil materials are subjected to surcharge loads (e.g. foundations), this compressible soil may experience settlements that may impact safety and performance of the proposed buildings. Therefore, improvement of the subgrade materials situated immediately below the proposed building footprint must be considered. Pile installation was not considered to be suitable for the subject site due to presence of the artesian groundwater.

Liquefaction

Potentially liquefiable soils are judged to be present within the subject site, which poses a potential geotechnical challenge, as liquefaction of soil materials supporting building loads may result in foundation failure and significant settlements.

Fig. 3. Water level monitoring at the piezometers with tidal elevation and daily pumping rate at the Town Well #1



Engineering Analyses

Seepage, deformation, and slope stability analyses were carried out to assess the site and subsurface conditions during and after construction of the proposed development.

Seepage analyses were carried out to establish a steady state groundwater condition. The results of the seepage analyses were used in deformation and slope stability analyses. Deformation analyses were carried out to estimate changes in subsurface stress conditions and ground movements, in the presence of the artesian groundwater pressures, as excavation is carried out. Slope stability analyses were carried out to estimate the overall stability of the slope from Gower Point Road towards the Gibsons Harbour during and after a seismic event.

Strength and deformation parameters were estimated based on the soil density/consistency values measured during the subsurface investigations.

Seepage Analyses

More than 90 seepage analyses were carried out to evaluate the potential impact of construction activities on the Gibsons Aquifer. The parameters were selected to be within accepted ranges for the soil types while ensuring that the pressures predicted for the Gibsons Aquifer were not underestimated.

The seepage model was used both to examine the relative sensitivity of model results to key parameters and to select a best-fit model for the deformation and slope stability analyses.

Following sensitivity analyses were carried out:

<u>Sensitivity to Gibsons aquitard hydraulic conductivity:</u> The importance of the Gibsons Aquitard hydraulic conductivity on the simulated groundwater flow behaviour under the subject site was assessed. Based on the results of the analyses, it was observed that the hydraulic conductivity of the Gibsons Aquitard plays a minor role in predictions of hydraulic head in the Gibsons Aquifer and groundwater discharge to the ocean.

<u>Sensitivity to Foreshore Parameters:</u> Overlying the seabed silty sand are the loose seabed sediments, as encountered at the locations of the test holes on the foreshore. Sensitivity analyses were carried out by assigning a range of hydraulic conductivities to the seabed sediments and different boundary head pressures. The predicted head pressures and groundwater flow discharge into the Gibsons Harbour were observed to be impacted directly by the foreshore parameters.

<u>Sensitivity to the Town Well #1 Head:</u> Analyses were carried out to evaluate the impact of the hydraulic head at the Town Well #1 on the groundwater flow process. In

these analyses, the magnitude of the boundary head at the Town Well #1 was increased, and the impact on the head pressures at the locations of bore holes and the groundwater discharge to the Gibsons Aquifer was assessed. The magnitude of the boundary head at the Town Well #1 was increased up to 18 metres, which based on the available information was considered reasonably conservative. As predicted, both head pressures and groundwater discharge to the Gibsons Aquifer were increased, as the head pressure at the Town Well #1 was increased.

Sensitivity to Gibsons Aquifer Hydraulic Conductivity: It had been observed that the Gibsons Aquifer, assumed to be composed of a single homogeneous unit, could have significant impact on the hydrogeology of the subject site. Increasing the hydraulic conductivity of the Gibsons Aquifer has significant impact on the groundwater discharge rate to the Gibsons Harbour. Using the results of the analyses, in conjunction to the available information, the Gibsons Aquifer was divided into three segments with different hydraulic conductivities, in order to have reasonable head pressures and groundwater discharge flows.

Sensitivity to Aquifer and Aquitard Contact: In addition to being controlled by local variations in the hydraulic conductivity of the Gibsons Aquifer, the hydraulic heads in the Gibsons Aquifer appear to be related to the thickness of the overlying aquitard. Therefore, the shape of the aquitard-aquifer boundary has an impact on the local scale head distribution predicted by the model within the Gibsons Aquifer. From the available data, areas within the aquifer that are overlain by thinner aquitard zones appear to have lower hydraulic head at the aquifer-aquitard boundary comparing to the areas with thicker aquitard layers.

Vertical Hydraulic Gradient: The seepage analyses were carried out with the objective of determining the potential for soil erosion failures due to the artesian pressures in the Gibsons Aquifer. Generally, piping failures occur when the upward force, such as artesian pressure, equals the weight of the soil confining the upward force. After the soil improvement at the subject site is carried out, the weight of the soil confining the Gibsons Aquifer pressure will exceed current conditions, and the potential for piping failures will be reduced. Results of this analysis is shown on Fig. 4.

Deformation Analyses

Selected results of the seepage analyses were used for deformation analyses. The deformation analyses were carried out for the purpose of determining the expected magnitudes of ground deformation at the base of the

Fig. 4. Piping analyses results before and after ground improvement

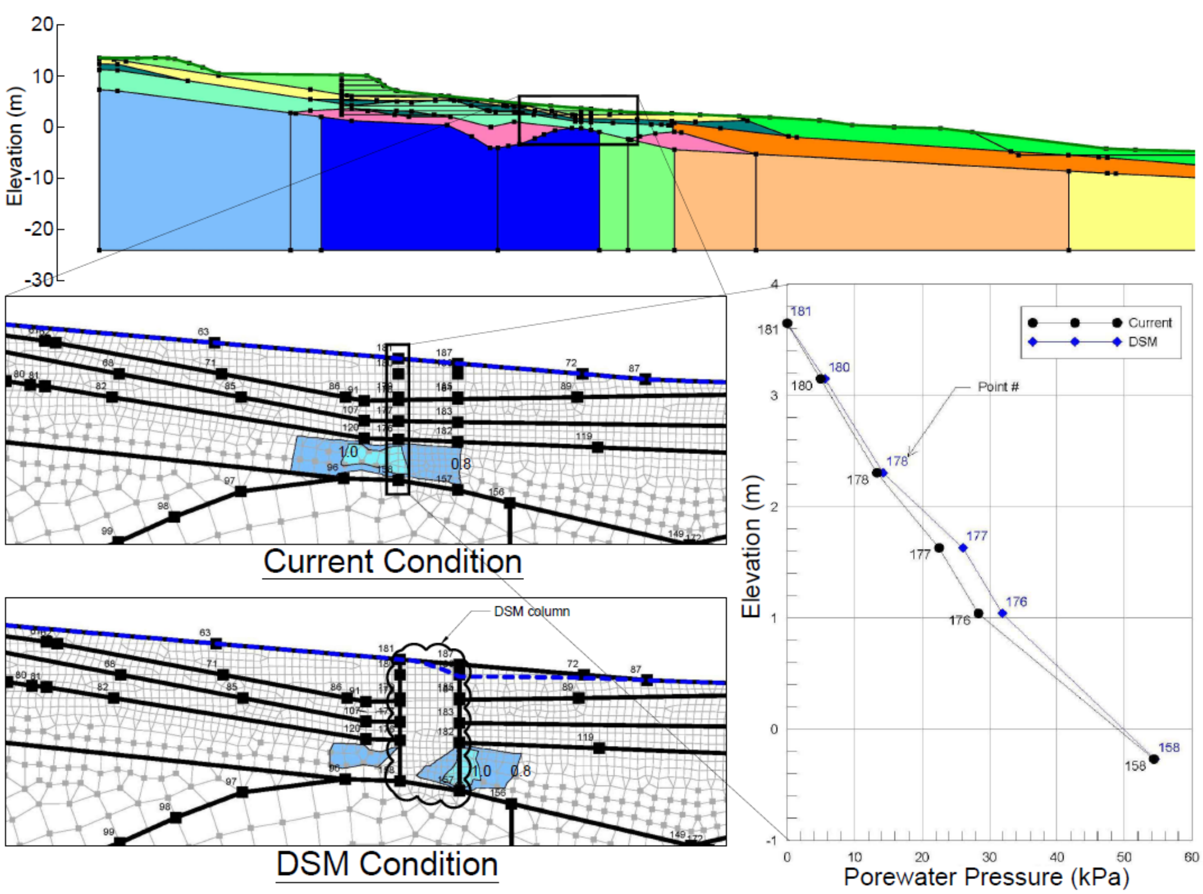
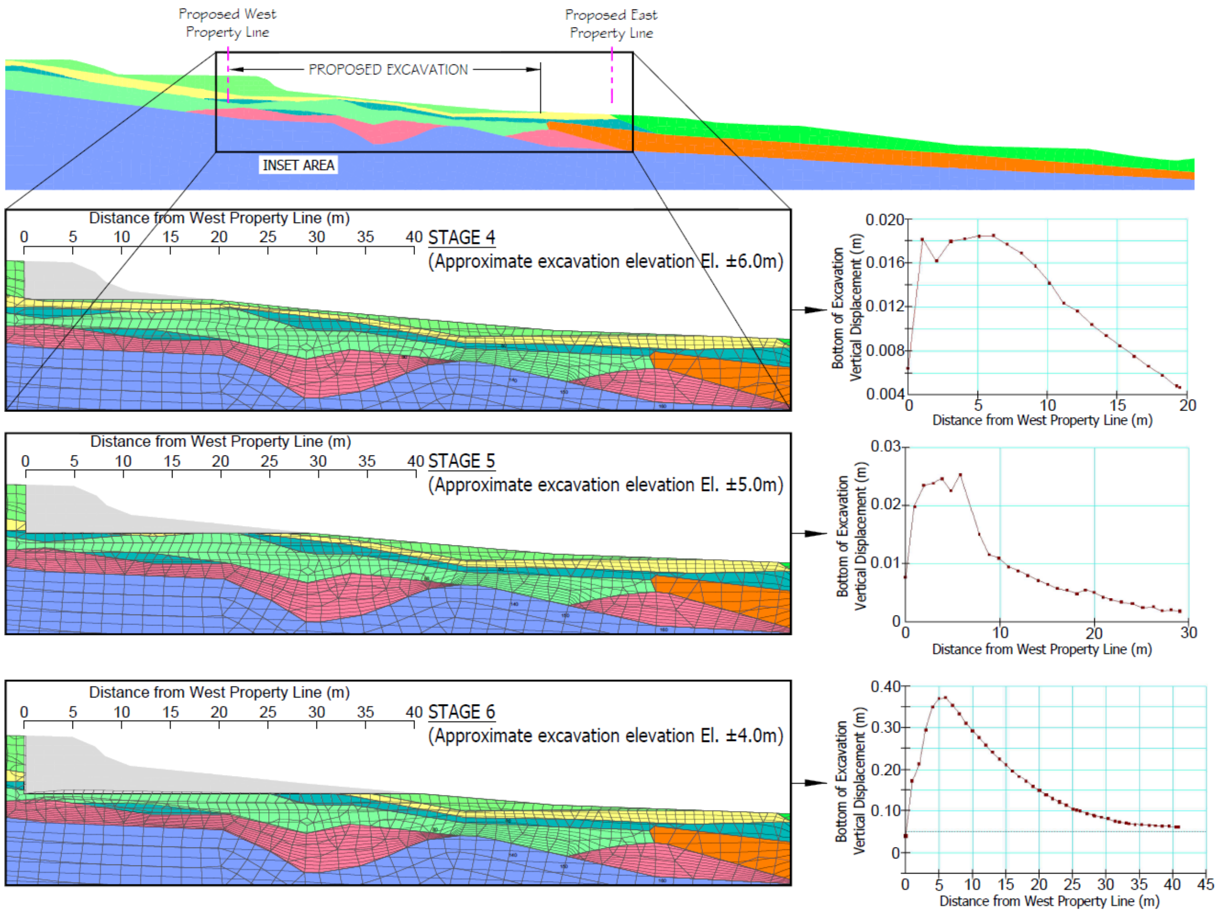


Fig. 5. Deformation analyses results during excavation



excavation that could result from the effects of the underlying artesian groundwater pressures within the Gibsons Aquifer. The deformation analyses were carried out in stages to simulate the progressive bulk excavation, and ground movements were estimated at each stage.

Based on the results of the deformation modelling, no traceable ground heave or subsequent tension cracks at the excavation surface are expected until the excavation is carried out to a depth of approximately 5.0 metres below the existing grade at the northwest portion of the site. Results of this analysis is shown on Fig. 5.

Based on the aforementioned analyses, excavation below an elevation of approximately 5.0 metres appears to have a tendency for local ground heaving, resulting in an unacceptable magnitude of ground heaving. Excavation for the balance of the site is limited to 0.5 metre from the existing grade.

Liquefaction Assessment

Analyses were carried out to assess the potential for liquefaction within the subject site, using the data collected from the subsurface investigations. The analyses results indicated that the soil profile at the footprint area of the proposed building was considered to be potentially liquefiable in zones ranging from approximately 0.3 to 3.4 metres thick.

The ground improvement, which was recommended for supporting the proposed foundations, will be designed to mitigate the liquefaction hazard beneath the proposed foundations. Therefore, subsequent to implementation of the proposed ground improvement measures, improved subgrade materials under the proposed footings are not expected to liquify during the design seismic event.

Seismic Slope Stability Analyses

As a part of the seismic assessment of the subject, stability of the subject slope during the design seismic event and for the post-liquefaction condition was assessed with and without ground improvement.

As discussed in previous section, the subsurface soil materials encountered at the subject site were considered to be potentially liquefiable during the design seismic event. However, the subgrade soil materials situated immediately below the proposed building footprint will be improved and will not be prone to liquefaction during the design seismic event. Select groundwater table and artesian pressures estimated in the seepage analyses, were used in the slope stability analyses.

In order to simulate the post-liquefaction slope stability, slope stability analyses were carried out using post seismic (residual) soil strength properties.

The analysis indicated that the existing slope is considered to be unstable during the design seismic event with Factor of Safety (FS) of less than 1.0. It indicated that a potential slip surface may initiate from Gower Point Road and terminates at the foreshore. The corresponding displacement along the slip surface during the design seismic event could be ranging from 0.3 to 0.6 metres.

The analysis indicated that the slope with the ground improvement would have FS of more than 1.0 under the design seismic event and for the post-liquefaction condition.

Building Foundation Concept

As mentioned before, we recommended that the proposed excavation not to be advanced below approximately 5.0 metres below the existing grade at the northwest portion of the site. At the balance of the site, we recommended that the proposed excavation not to be advanced below 0.5 metre below the existing grades. This is to reduce the potential compromising the Gibsons Aquifer due to excavation of the overlying soil materials.

The subgrade soil materials that are expected to be exposed at the site are envisaged to comprise fill, peat, sand, and silty sand to sandy silt to silt. Till-like silty sand to silt to sand materials are not expected to be exposed at the proposed foundation elevations.

Therefore, we recommended that foundations for the entire building footprint are supported on conventional strip and pad foundations or on a raft foundation. Due to the presence of loose and compressible subgrade materials (which are not suitable for supporting shallow foundations in their current state), either the proposed foundation loads should be transferred down to a suitable bearing stratum or some form of ground improvement should be implemented. The use of deep foundations may be appropriate for this site, but due to the potential impact of deep foundations on the aquifer during or after installation, ground improvement is judged to be the more suitable option to provide support for the proposed foundations.

Ground Improvement

Based on a review of the available reference documents prepared by the project design team, a list of risk items pertaining to the ground improvement components was compiled with an assessment considering the three main options for ground improvement for foundation support comprising Conventional Deep Mixing (DMM), Deep Mixing using Cutter Soil Mixing (CSM), and Excavation and replacement under Self-Hardening Slurry (SHS).

Based on a project-specific assessment of the construction related risks and considering the main goal, which is to provide ground improvement for foundation support for the hotel and residences whilst safeguarding the integrity and quality of the Gibsons Aquifer, the construction methodology to be adopted for DM requires careful assessment. Of the options mentioned above, based on the need to reduce the risk of breaching the underlying confined aquifer, and having specialized consultant and contractor on the project team, CSM was recommended to be pursued.

Ground improvement process would terminate in compact to dense soil materials, which are expected to comprise silty sand, till-like silty sand to silt and sand, or the sand and gravel to gravel. It is noteworthy that neither of the above-mentioned methods involve removal of the soil. Therefore, we envisage that the aquifer-confining effects of the aquitard materials would not be compromised during either process.

In general, DM involves penetrating into the unsuitable subgrade soil materials with specialized equipment and subsequently introducing grout into the hole, which is mechanically mixed with the disturbed soil to create a soil-cement element. Deep mixing method would maintain the aquitard’s properties that resist the underlying artesian pressures of the Gibsons Aquifer (i.e., overburden pressure and hydraulic conductivity) throughout the installation and curing process. No voids would be created during this process, which could otherwise create a potential preferential flow path for artesian groundwater. Although the aquitard material would be disturbed, its hydraulic conductivity would not be increased. As a result, we do not envisage that there is a physical mechanism possible during DM installation that would allow artesian groundwater from the underlying Gibsons Aquifer to enter the DM system. Based on the numerical analyses results, we concluded that, piping was not anticipated to occur within the DM system during or after installation.

Horizon Engineering carried out laboratory tests on the soil samples obtained from the excavation of test pits. Soil samples comprised silty sand and sand materials. Soil materials were mixed with cement at different ratios and were tested to estimate the unconfined compressive strength. The 28-day unconfined compressive strengths, for different soil-cement ratios, were estimated to be in the range of 1.2 to 3.3 MPa.

A full-scale field trial was proposed to be carried out to verify that the construction methodology, proposed mix design and aquifer protection plan, meet project performance requirements and provides confirmation that a breach of the confined aquifer will not be taken place.

Contingency Plan to Protect Aquifer

Horizon Engineering does not expect a significant breach / disturbance of the aquifer. In an event that minor ground heaving and/or upward groundwater seepage are observed during the excavation/construction, contingency plan to protect the aquifer would be in place, that would include utilizing the existing piezometers and drilling additional case auger holes to de-pressurize the aquifer locally. The need for installing additional drawdown auger holes can be assessed during DM large-scale field trial.

Summary of Conclusions and Recommendations

From a geotechnical point of view, the subject site is considered to be suitable for development of the type proposed, and the Gibsons Aquifer is envisaged to not be negatively impacted by the proposed development.

The Town of Gibsons and the subject site are underlain by the Gibsons Aquifer, which is a confined aquifer comprising sand and gravel that provides drinking water for the town. The confining Gibsons Aquitard is inferred to comprise variable thicknesses of sand, peat, silty sand to sandy silt to silt, and localized till-like materials within the subject site.

Artesian groundwater pressures have been observed within the Gibsons Aquifer. Hydraulic connections have been observed between the Gibsons Aquifer and the ocean at the central portion of the site and between the Gibsons Aquifer and the Town Well #1 at the west portion of the site.

Engineering analyses comprising seepage, deformation, and slope stability were carried out to determine the stability of the site, and the magnitude of excavation of the overlying materials that could be carried out such that the underlying Gibsons Aquifer is not compromised due to excavation was estimated.

We recommend that foundations for the entire building footprint are supported on conventional strip and pad foundations or on a raft foundation. Due to the presence of loose and compressible subsurface soil materials, ground improvement was recommended beneath the proposed foundations such that suitable bearing is achieved. We concluded that DM using Cutter Soil Mixing may be the preferred method of ground improvement at the subject site.

The soil profile at the footprint area of the proposed building is considered to be locally potentially liquefiable; however, we envisage that after implementation of the proposed deep soil mixing ground improvement measures, the potential for liquefaction beneath the proposed building foundations would be eliminated.

Construction for this project is expected to start in Summer 2018.

References

Doyle, J. 2013. Integrating Environmental Tracers and Groundwater Flow Modeling to Investigate Groundwater Sustainability, Gibsons, BC, Master of Science Thesis, University of British Columbia.

Waterline Resources Inc. 2013. Aquifer Mapping Study – Town of Gibsons, British Columbia.