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Load-deformation analysis on a slope at Gunung Pulai water treatment plant, Sultan Ibrahim Reservoir

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Abstract. The Sultan Ibrahim Reservoir located at Gunung Pulai catchment area was previously managed by the Singapore's Public Utilities Board before the Board handed over the reservoir to Johor State Government under current management of the Syarikat Air Johor. At the present time, the Syarikat Air Johor is operating a Gunung Pulai Water Treatment Plant consisted of two main plants, i.e. Water Sedimentation Plant and Water Filtration Plant for treating raw water from the reservoir before supplying to the consumers. However, the integrity of water treatment plant's structure should be checked due to several cracks were observed, and moreover the structure was built over more than 90 years. The formation of the cracks in the Gunung Pulai Water Treatment Plant may be induced by movement of the sloping area to the south-east of Water Sedimentation Plant. The calculated Factor of Safety (FOS) via sensitivity analysis for cross sections of original slope indicates any decrease in friction angle and/or cohesion strength or increase in horizontal seismic load will further cause instability on slope. Also, the results of Load-Deformation analysis on cross sections of original slope show significant vertical displacement and horizontal displacement on the bottom and both sides of sedimentation tanks, respectively. The results indicate applied structural and water loads significantly affect deformation at both vertical and horizontal directions which could have contributed to FOS < 1 in slope stability analysis.

1. Introduction

Sultan Ibrahim Reservoir was built within 1924 to 1929 located at Gunung Pulai catchment area. The reservoir has 130 acres of lake with a maximum capacity of 1220 million gallons of water. A dam was built to retain water where the geometry of the dam is 36.6m height and 182.3m length. Also, the Gunung Pulai Water Treatment Plant (GPWTP) is situated near the Sultan Ibrahim Reservoir to treat raw water from the reservoir before supplying to the consumers. The GPWTP was built and previously managed by the Singapore's Public Utilities Board (PUB) for more than 50 years and it was handed over to the Johor



State government under new management of the Syarikat Air Johor (SAJ). However, the integrity of the water treatment structure should be checked due to the structure was built over more than 90 years, and moreover after a several cracks was recently observed at Water Sedimentation Plant as shown in Figure 1 and Figure 2.

Two (2) possibilities could have contributed to the cracks which are the effect from vibration due to blasting activities from the nearby quarry and/or the movement of present retaining wall or sloping area nearby the treatment plant. To measure and quantify the vibration, real time monitoring is conducted in order to understand on the vibration effect toward the treatment plant structure. The implementation of slope monitoring program and installation of vibration monitoring devices at Gunung Pulai Water Treatment Plant (GPWTP) that include designing, setting-up and installing multiple monitoring systems with the aim of identifying contributed factors to the problem of crack on water treatment structures, i.e. Water Sedimentation Plant (Kassim *et. al.*, 2018a).



Figure 1. Water sedimentation plant.



Figure 2. A structural crack was observed on the Water Sedimentation Plant storage tanks.

2. Site investigation works and slope characterisation

The rotary boring was carried out in accordance to the British Standard Code of Practice BSI 5930: 1999 – “Site Investigation” and laboratory tests are accordance to BSI 1377: 1990. Altogether four (4) numbers of boreholes were conducted at the proposed site as shown in Figure 3. The borehole was advanced by mean of Rotary Boring Machine (YWE). However, due to condition on site, none of pneumatic piezometer and inclinometer has been successfully installed.

The geophysical survey works for site investigation works using electrical resistivity survey using 2-D electrical resistivity was also employed. The exact locations, longitude and latitude of the transverse survey points were determined in the field with the help of Global Positioning System (GPS), Garmin Model. The horizontal accuracy of GPS is nearly 3m-4m when the strong satellite signals were detected. The alignment of resistivity Line 1, Line 2 and Line 3 begin at electrode 1 (E1) and end at electrode 41 (E41) with coordinates shown as in Table 1 (Kassim *et. al.*, 2018b). The resistivity data was processed with RES2DINV software, a computer program, to automatically determine a two-dimensional (2D) resistivity model for the subsurface for the data obtained. Results of the resistivity survey along the proposed alignment are presented in images as shown in Figure 4. The maximum depth of the images exceeded 35 m at the center of the line. The image of each line was briefly interpreted to describe the subsurface based on resistivity value of geo-material (Telford & Sheriff, 1984).

The resistivity images in Figure 4 show a subsurface profile along 200m of resistivity Line 1, Line 2 and Line 3. The images show that the subsurface material of Line 1 is dominantly underlain by resistivity

value less than $500\Omega\text{m}$ around the centre of the line that can be interpreted as completely weathered rock or soil. Significant low resistivity zone (less than $50\Omega\text{m}$) was identified at 40m (60m from E1) from the center of the Line 1 that interpreted as saturated zone. The depth of saturated zone is estimated 7m from the surface. The image also shows that the subsurface material of resistivity value ranging above $1000\Omega\text{m}$ can be interpreted as hard layer of weathered rock or boulders. The hard layer is shown overlain the area.

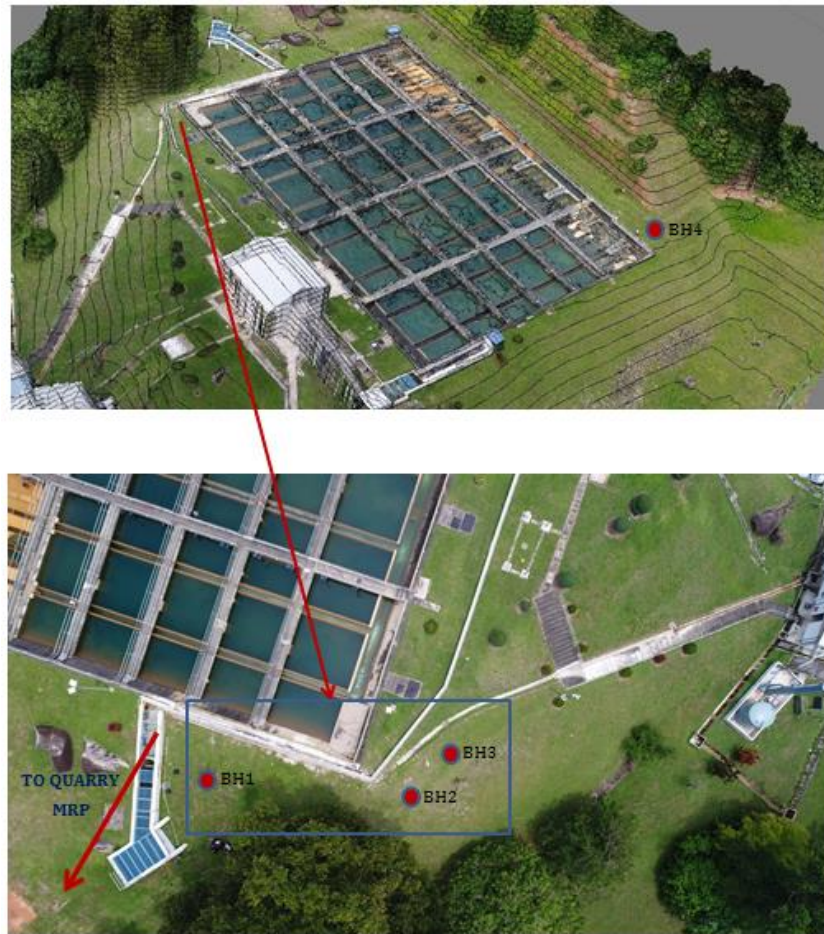


Figure 3. Location of BH1, BH2, BH3 and BH4.

Table 1. Summary of coordinates for resistivity lines. (Kassim *et. al.*, 2018b)

Resistivity Line	Coordinates		Length (m)
	Start Point (E1)	End Point (E41)	
Line 1	N 01°33.764' E 103°34.010'	N 01°33.853' E 103°34.053'	200

Line 2	N 01°33.895' E 103°34.093'	N 01°33.934 E 103°34.184'	200
Line 3	N 01°33.945' E 103°34.105'	N 01°34.030' E 103°34.155'	200

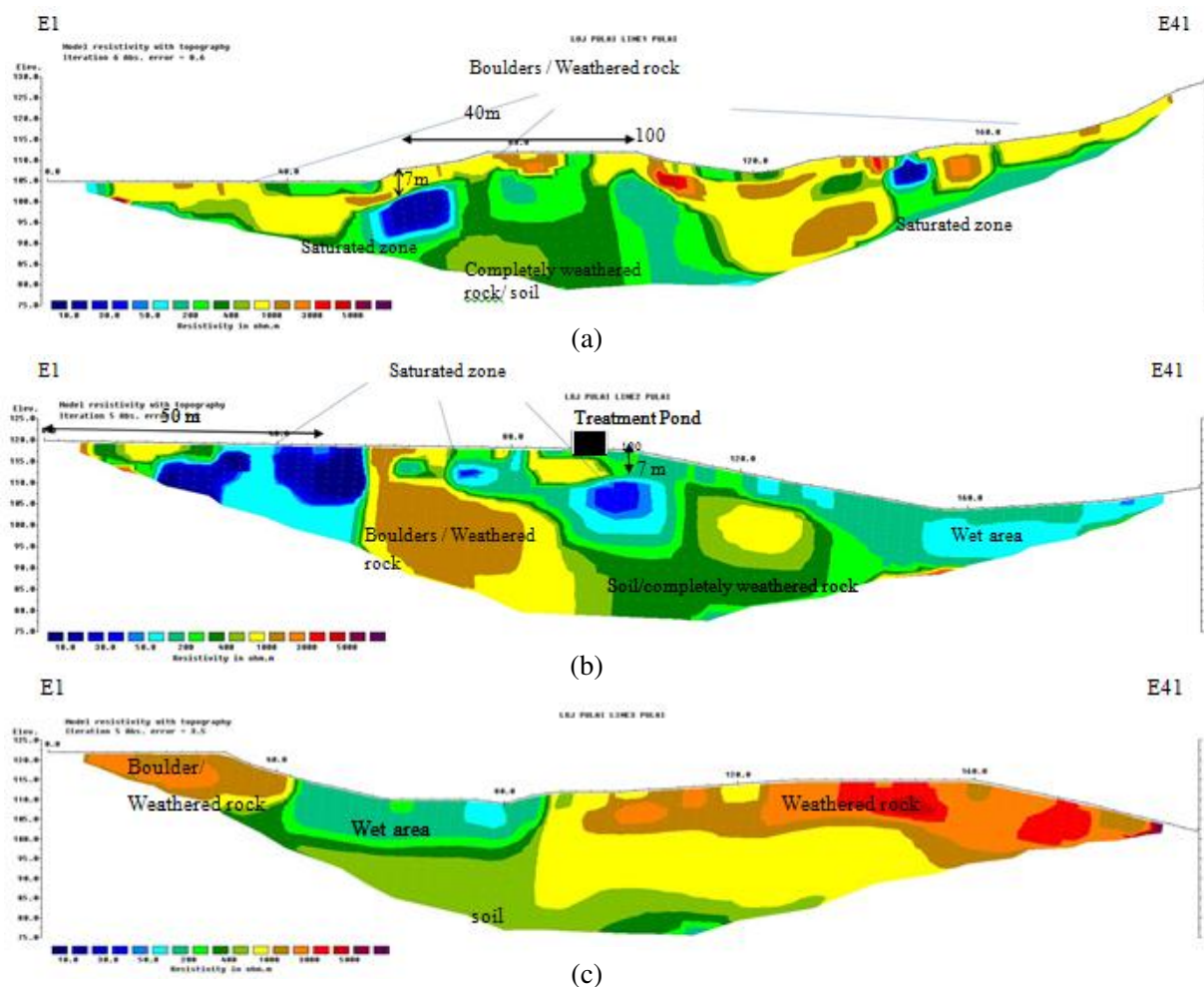


Figure 4. Resistivity image of Line 1 (a), Line 2 (b) and Line 3 (c) (Kassim *et. al.*, 2018b).

Line 2 is dominantly covered by low resistivity value material which is less than $400\Omega\text{m}$ interpreted as soil or completely weathered rock. The significant very low resistivity (less than $50\Omega\text{m}$) was found 50m from E1 considered as saturated zone where consider as soil with high water content. The saturated area is believed to be confined by the hard material (boulders). Saturated zone was also detected at the center of survey line which is next to the water treatment pond. And lastly, Line 3 shows that subsurface material is dominantly underlain by high resistivity material (more than $1000\Omega\text{m}$) that can be interpreted as hard and

weathered rocks. It is believed that there is soil layer underlain the boulders. It can be observed at the upper part of subsurface profile at the distance of 45m to 90m from E1 there is a location of low resistivity area which considered as wet area where it is considered high water content in the soil here.

3. Slope stability analysis

Rainfall-induced failures in residual soil slope are common in tropical or subtropical climates that experience periods of intense or prolonged rainfall (Huat *et al.*, 2005; Shaw-Shong, 2004; Brand, 1984). In Malaysia, the most common type of these failures is the shallow slide typically 1.0 m to 1.5 m depths occurs during or immediately after intense rainfall, and the slip surfaces are frequently orientated parallel to the slope surface (Ali Jawaid, 2000; Abdullah & Ali, 1994).

In general, the existing slope in the Water Sedimentation Plant is relatively steep with the average slope angle ranges from 27° to 30° . Since the friction angle, ϕ for top soils – Silty SAND obtained from site investigation works ($\phi' = 20^\circ$) is lower than the average slope angle, the existing slope is expected to be unstable and unsafe, and erosion could occur due to present of loose top soil on slope and high rainfall intensity during monsoon season (Kassim *et al.*, 2012; Lee *et al.*, 2011).

Figure 5 shows two slope cross section, C1 and C2 where the original slope has a slope height of 25m and slope angle of 27° . The original slope profile and soil properties are interpreted from nearby BH1, BH2, BH3 and BH4 as shown in Figure 3 (Kumpulan Ikram, 2018). The geometry and soil profile consist of two main layers of Top Soil firm to stiff Silty SAND (unit weight, $\gamma = 16\text{kN/m}^3$, effective friction angle, $\phi' = 20$, effective cohesion, $c' = 5\text{kPa}$, Young Modulus, $E = 3000\text{kPa}$ and Poisson's ratio, $\nu = 0.4$) and Bottom Soil stiff to very stiff Weathered Rock ($\gamma = 24\text{kN/m}^3$, $\phi' = 35$, $c' = 0\text{kPa}$, $E = 30000\text{kPa}$ and $\nu = 0.3$). There are 2 type of analysis carried out on C1 and C2, i.e. Factor of Safety (FOS) distribution analysis via sensitivity on seismic load (k_h), γ , ϕ' and c' and Load-Deformation analysis on original slope with treatment plant full with water.

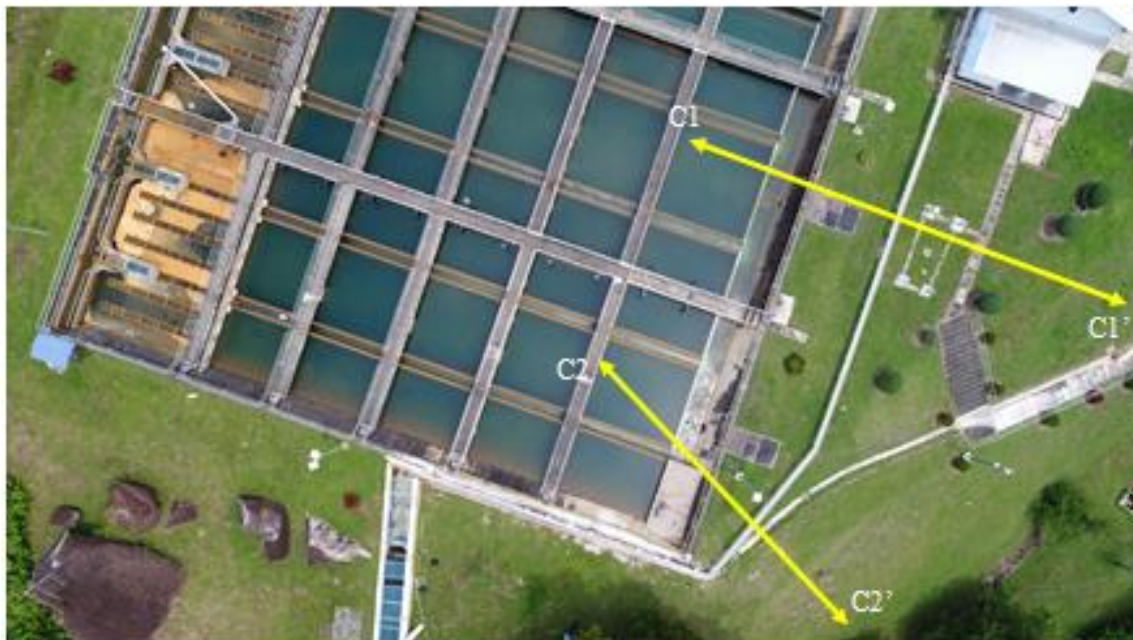


Figure 5. Slope cross section of C1 and C2.

The total dimensions of sedimentation tank are 45m (Width) x 7m (Depth) with inclined concrete wall of 45° and unit weight of water is taken constant as 9.807kN/m³. The analysis are carried out by using two commercial softwares, i.e. (1) SLOPE/W (GEO-SLOPE, 2012a) to model and carry out Limit Equilibrium analysis (FOS) and (2) SIGMA/W W (GEO-SLOPE, 2012b) to model and carry out Load-Deformation analysis.

Figure 6(a) and (b) shows the calculated Factor of Safety (FOS) for cross section C1 and C2. The slope stability analysis show the failure feature for cross section C1 is likely global and deep seated with the FOS = 0.864 via sensitivity analysis. The FOS = 1 (stable condition) with sensitivity of k_h , ϕ' and c' at 0.21g, 24° and 10kN/m³, respectively on top soil (Silty SAND) but FOS is not sensitive to bottom soil (Weathered Rock) as shown in Figure 7. The results for cross section C1 indicate any decrease in ϕ' and c' (during wetting/saturated condition) or increase in k_h will cause instability on slope (FOS is less than 1).

Also, the failure feature for cross section C2 is likely global and deep seated with the FOS = 0.608 via sensitivity analysis. Figure 7 shows the FOS < 1 for all k_h , ϕ' and c' values to show original slope at cross section C2 is unstable. However, the sensitivity trends are similar to cross section C1 where it is sensitive to top soil but FOS is not sensitive to bottom soil. The results indicate the slope at C2 is likely to fail to compare to FOS for C1 = 0.864.

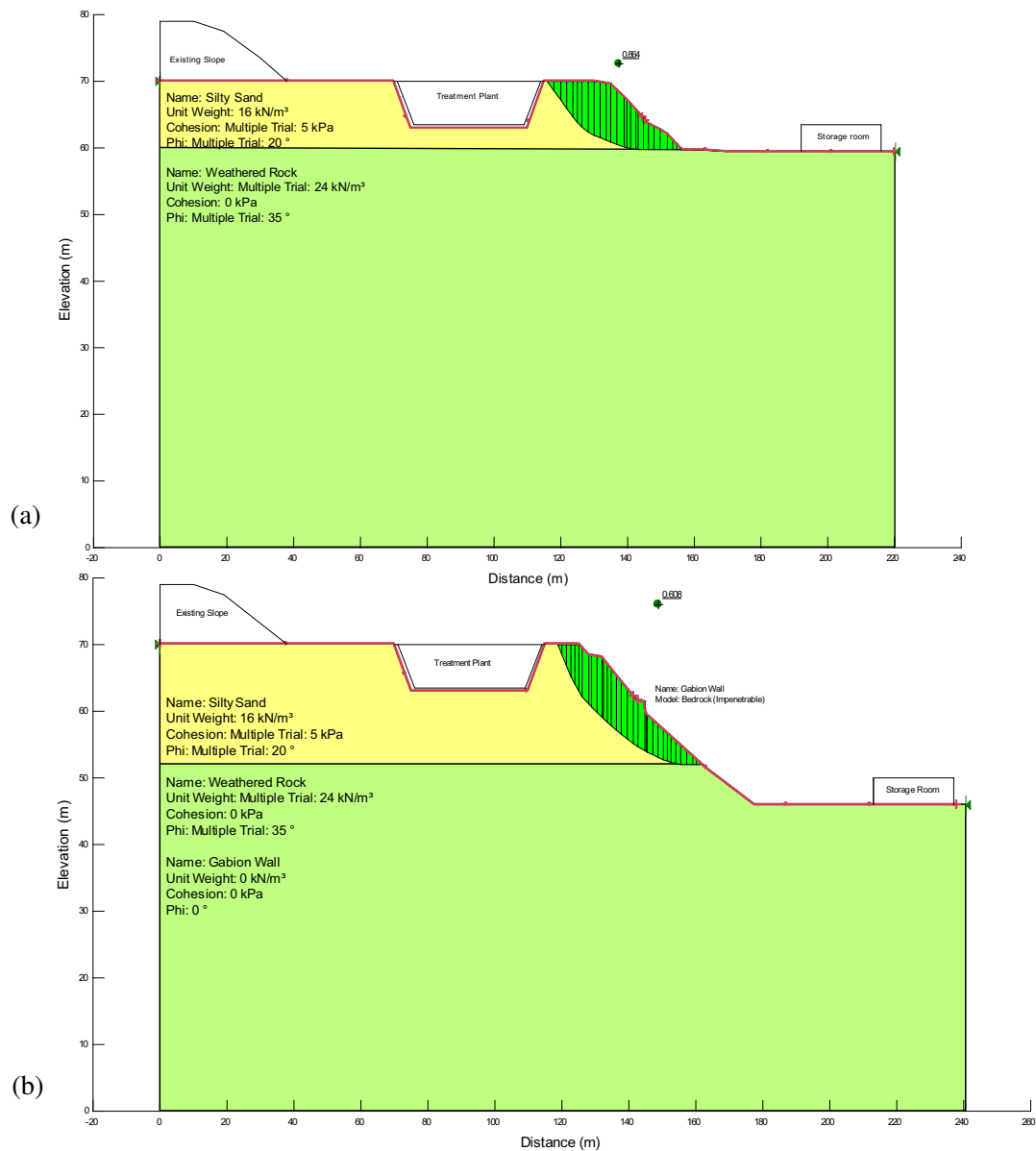


Figure 6. Slope stability analysis on C1(a) and C2(b).

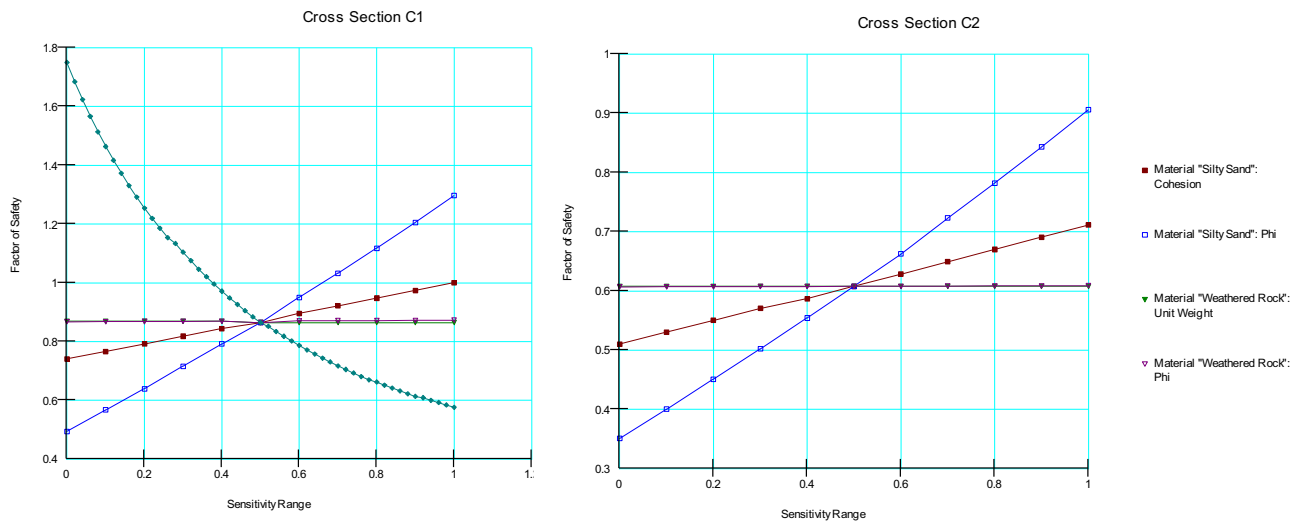


Figure 7. Sensitivity analysis on C1 and C2.

Figure 8 to 10 shows the results of Load-Deformation analysis on cross section C1 and C2. The results of analysis show the vertical displacement on cross section C1 is maximum on the bottom of treatment plant (Y-displacement = 110mm) but decreasing to 0mm at Reference Level of 0m. The horizontal displacement, X-displacement = 10mm to 60mm on cross section C1. The results for cross section C1 indicate applied load significantly affect deformation at both vertical and horizontal directions which could have contributed to FOS < 1 in slope stability analysis. For cross section C2, the maximum vertical displacement (Y-displacement) = 200mm is larger than found on C1 (Y-displacement = 110mm). The horizontal displacement on C2, X-displacement = 60mm to 150mm as shown in Figure 10. The results indicate deformation due to applied load is more critical at cross section C2 to compare to cross section C1.

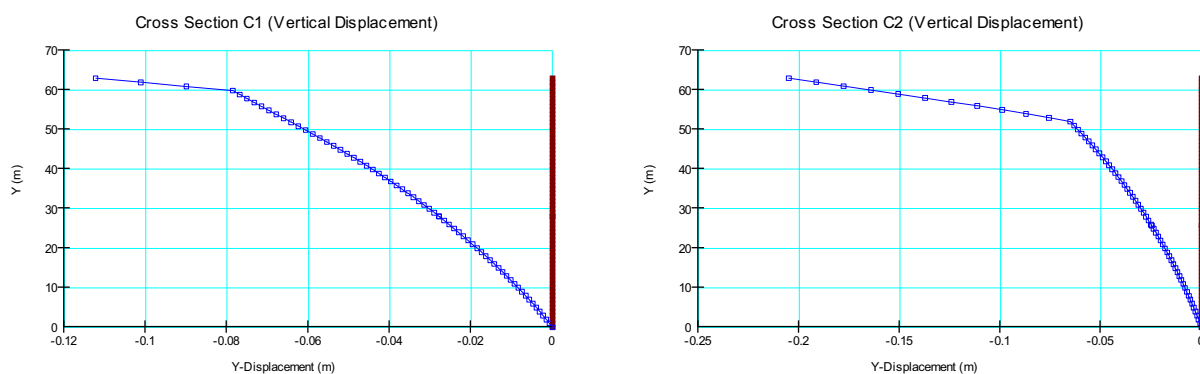


Figure 8. Vertical displacement on C1 and C2.

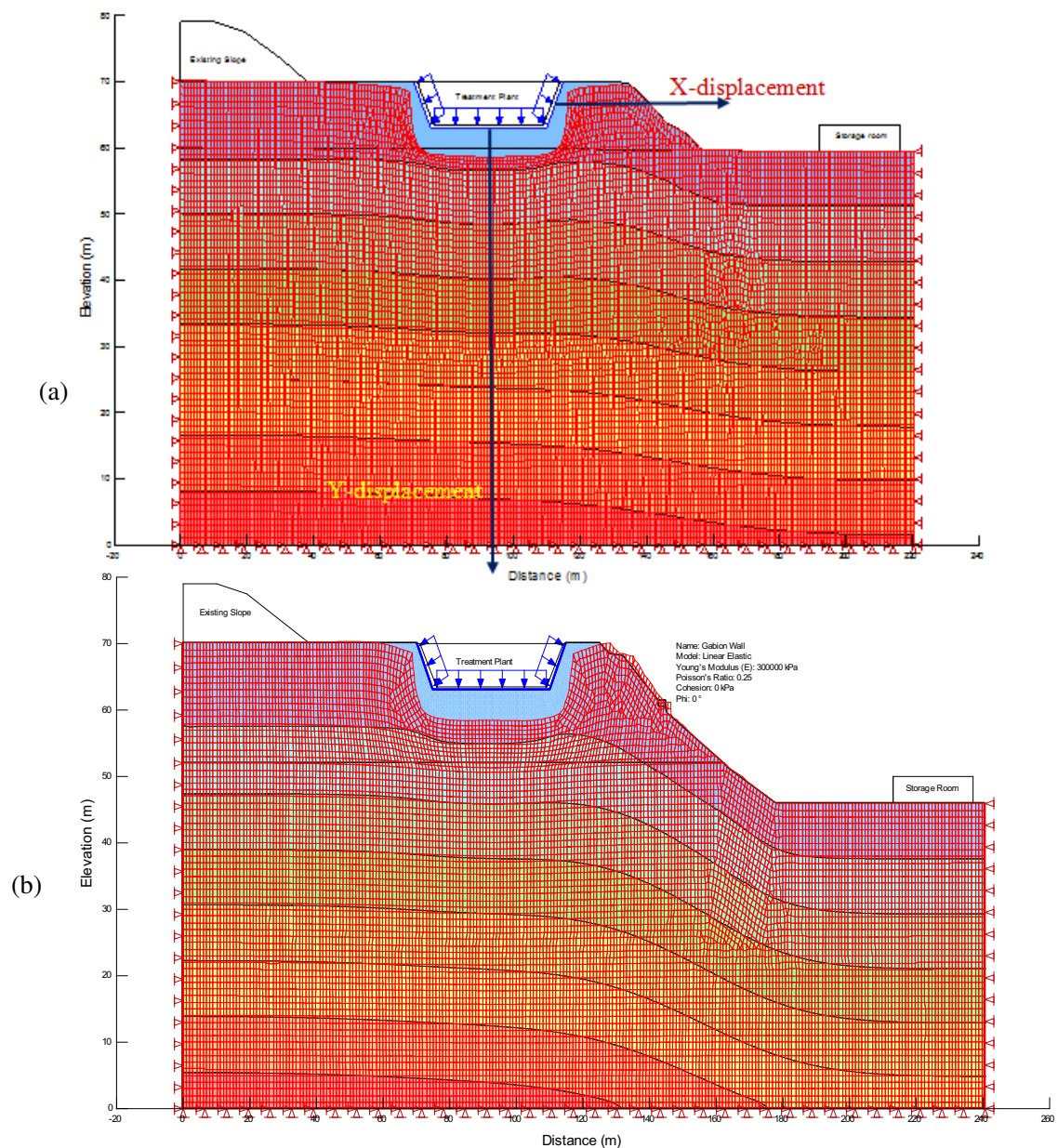


Figure 9. Load-Deformation analysis on cross section on C1(a) and C2(b).

4. Conclusions

The calculated Factor of Safety (FOS) via sensitivity analysis for cross sections of original slope shows the failure feature is likely global and deep seated with sensitivity analysis results indicate any decrease in ϕ' and c' during wetting/saturated condition and/or increase in k_h will further cause instability on slope. The results of Load-Deformation analysis on cross sections of original slope also show maximum vertical displacement on the bottom of treatment plant but decreasing to 0mm at Reference Level of 0m, and horizontal displacement is also decreasing from 150mm to 10mm toward the slope. The results indicate

applied structural and water loads significantly affect deformation at both vertical and horizontal directions which could have contributed to $FOS < 1$ in slope stability analysis. It is also shown that deformation due to applied loads is more critical at cross section C2 (near corner area of Water Sedimentation Plant) to compare to cross section C1.

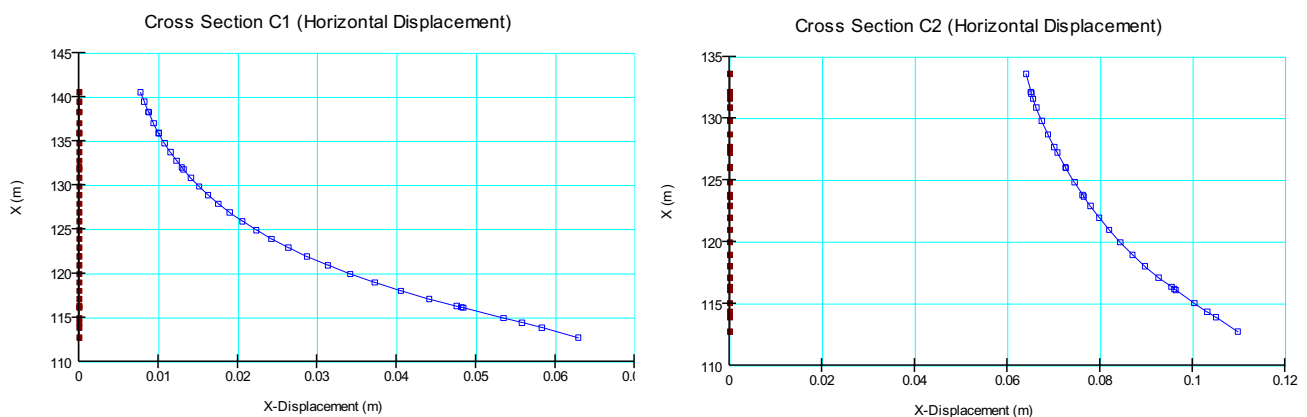


Figure 10. Horizontal displacement on C1 and C2

Therefore, it is strongly recommended that slope remedial works (designing and constructing stable slope) together with in depth investigation on crack of sedimentation concrete structure (repairing and monitoring of crack propagation) should be carried out in very near future. The most importantly, the slope at corner area should be reinstated to strengthen gabion wall before the cracks on that particular location of Water Sedimentation Plant are repaired.

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