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Classical Method and Numerical Modeling for Designing of Sheet Pile Wall (Case Study: Tuti-Bahri Bridge, Sudan)

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Abstract
Sheet piling is an earth retention and excavation support technique that retains soil, using steel sheet sections with interlocking edges. The purpose of this paper is to provide an acceptable design method and theory for the geotechnical design or anchored sheeting pile walls to be constructed on abutment and embankment of Tuti-Bahri Bridge project. The design procedures included in this document are in common use today by most engineers involved in the design of sheet pile retaining structures. These methods have consistently provided successful retaining structures that have performed well in service. Two methods, classical design method and numerical method was used in this study. The forces in sheet pile and anchor calculated by using these methods. Then safety factor obtained by using numerical modeling. The results showed that this area is stable by using sheet pile and anchor in static and earthquake conditions. Then, the properties of steel pile and steel anchor suggested by considering the classical and numerical results.

Keywords: Sheet Pile, Anchor Force, Classical Method, Numerical Modeling

Introduction

In geotechnical practice, cantilever embedded retaining structures are specifically used for protecting permanent and temporary excavations, for highway construction, and sanitation of landslides. These structures are mostly sheet walls as temporary retaining structures, and pile walls and diaphragms as permanent retaining structures. Sheet piles are widely used as retaining structures, especially in excavation projects.

Sheet pile walls consist of continuously interlocked pile segments embedded into the soils to resist horizontal pressures. The sheet pile walls are constructed by driving the sheet piles into a slope or excavation. They are considered to be most economical where retention of higher earth pressures of soft soils is required.

Sheet piles can function as temporary or permanent structures and are most often used in excavation projects. Temporary sheet piling structures are used to control or exclude earth or water and allow the continuation of permanent work. Permanent sheet piling is commonly used as a retaining structure, and at times as part of the structure of underground buildings (Paikowsky & Tan 2005).

At present time, among the available solutions in the market, the usage of steel sheet pile walls is a widespread used solution in marine and coastal constructions, especially as quay walls (Osório et al., 2010). This is mainly due to the fact that sheet pile walls are easily installed within short time, can produce a watertight wall (Eskandari & Kalantari, 2011) and the environmental impacts are minimum.

Although retaining walls are used frequently on excavations and thus their design approaches and methods are deeply studied, its behavior in backfill construction is still not as much understood and predictable (Bilgin, 2010). Actually, the current design procedures used in sheet pile walls are based on limit equilibrium approaches that make use of active and passive earth pressures, related to the Mohr-Coulomb failure criterion. However, these do not take into account the construction procedures which may cause different loading conditions in the soil and consequently dissimilar behavior of the structure. This way, conventional assumptions and tools, such as the Rowe moment reduction curves used to calculate design moment, might not be valid in backfilling conditions since they are based on tests simulating walls in excavation conditions (Bilgin, 2010).

Numerical modelling has evolved over the years. Research has found that these numerical methods for the design of sheet pile walls are very useful and can be used to obtain information that is unavailable when using analytical methods for the design of sheet pile walls (Smith 2006; Bilgin 2010); that is, the wall deformation, ground settlement and possible surface failures. Škrabl propose a new method for the geomechanical analysis and design of cantilever retaining structures. It is based on the limit equilibrium method, but it uses some additional conditions for interaction between the retaining structure and the ground, when referring to the distribution of the mobilized earth pressures on the structure (Škrabl, 2006). In this paper, classical and numerical methods are used for providing an acceptable design method and theory for the geotechnical design or anchored sheeting pile walls to be constructed on abutment and embankment of Tuti-Bahri Bridge project.

Lithological Modeling of the Ground

Because sheet pile walls derive their support from the surrounding soil, an investigation of the foundation materials along the wall alignment should be conducted at the inception of the planning for the wall.

Based on the geo-technique report, the properties of the different layers of the geology are illustrated in Table 1.

Classical design method

There are several design methods that make different assumptions and hence make different simplifications of the net pressure distribution exerted along the sheet pile wall. In this section, the classical design methods of sheet pile walls are discussed. The current limit state design method most commonly used in the United Kingdom (UK) is the UK method, as described by Padfield and Mair (1984). In the United States (US), the USA method, or gradual method, as described by Bowles (1996), is the most commonly used limit state design method. Suggesting a rectilinear pressure distribution leads to the simplifying of the net pressure distribution along the sheet pile wall. An analytical limit equilibrium approach has been suggested by King (1995), involving an empirically determined parameter. The net pressure distribution has been examined using finite element analysis by Day (1999).

Table 1: Geotechnical properties of the different layers

STRATA	Loose silty sand	Medium silty sand	sandstone	mudstone
Bulk modulus K (MPa)	420			
Shear modulus G (MPa)	190			
Angle of friction Φ (deg)	30	35	40	30
Cohesion c (kPa)	30	100	300	400
Unit weight ρ (kN/m^3)	2000			

Earth Pressure

The stress state in each point of the sheet pile wall depends on the movement produced.
In order to define the earth pressure at failure conditions, the Rankine states are used.
When a sheet pile wall is introduced and an excavation is done, the earth pressure generated can be produced in two ways (US-Army, 1994 & B.M. Das, 2016):
- Active pressure (Ka): The soil exerts a pressure against the wall. The wall moves to the excavation and the horizontal stress decreases, as the vertical stress remains unchanged. A decompression in the horizontal stress occurs. In a limit situation, a failure wedge is formed, producing a plastic regime. The earth pressure is lower than in the at-rest state.
- Passive pressure (Kp): The wall exerts a pressure against the soil. In this case the horizontal stress increases, while the vertical stress remains unchanged. Therefore, the earth pressure is higher than in the at-rest state. In a limit situation, a failure wedge is formed as well, but with greater dimensions than in the active case.
The resulting earth pressure diagram for a homogeneous granular soil is shown in Figure 1 where the active and passive pressures are overlain to pictorially describe the resulting soil reactions.

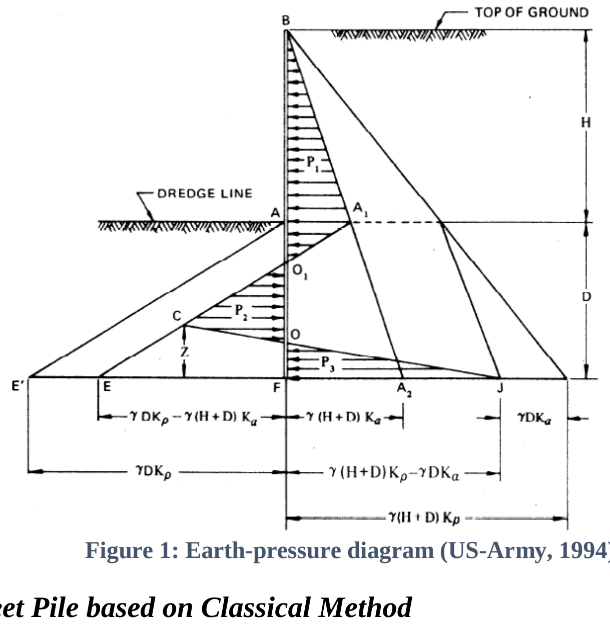

Figure 1: Earth-pressure diagram (US-Army, 1994)

Designing Sheet Pile based on Classical Method

The classical method for designing sheet pile in with and without surcharge conditions are shown in Figure 2. The coefficient of active and passive pressure are calculated based on the Rankin's theory (US-Army, 1994 & Das. B.M, 2016).

$$K_a = \tan^2\left(\frac{\pi}{4}-\frac{\varphi}{2}\right), K_p = \frac{1}{K_a} \quad (1)$$

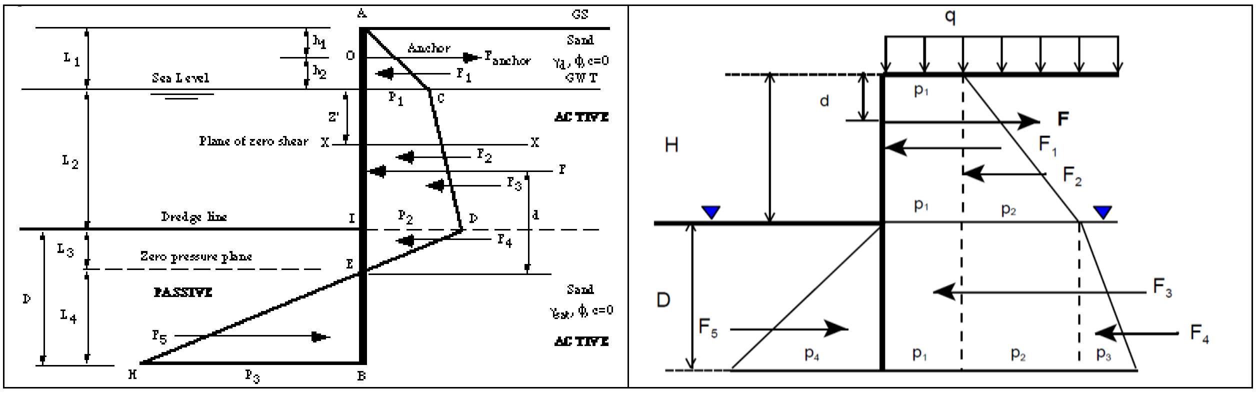

Figure 2: Design of anchored sheet pile wall penetrating in sand without and with surcharge condition

The process of calculating the parameters are presented in the following for without surcharge condition (US-Army, 1994 & Das. B.M, 2016).

$$P_1 = \gamma L_1 K_a \quad (2)$$
$$\gamma_{eff} = \gamma_{sat} - \gamma_w \quad (3)$$
$$P_2 = (\gamma L_1 - \gamma_{eff} L_2) K_a \quad (4)$$
$$L_3 = P_2 \Big/ \gamma_{eff}(K_P - K_a) \quad (5)$$
$$F_1 = 0.5 P_1 L_1 \quad (6)$$
$$F_2 = P_1 L_2 \quad (7)$$
$$F_3 = (P_2 - P_1)\frac{L_2}{2} \quad (8)$$
$$F_4 = 0.5 P_2 L_3 \quad (9)$$
$$F = F_1 + F_2 + F_3 + F_4 \quad (10)$$
$$d = \frac{1}{F}\left[F_1\left(\frac{L_1}{3}+L_2+L_3\right)+F_2\left(\frac{L_2}{2}+L_3\right)+F_3\left(\frac{L_2}{3}+L_3\right)+F_4\left(\frac{2L_2}{3}\right)\right] \quad (11)$$
$$A_1 = 1.5\left(h_2 + L_2 + L_3\right) \quad (12)$$
$$A_2 = 3F\left[\frac{(L_1+L_2+L_3)-(d+h_1)}{\gamma_{eff}\left(K_p - K_a\right)}\right] \quad (13)$$
$$L_4^3 + A_1 L_4^2 - A_2 = 0 \quad (14)$$

The theoretical depth (D), the actual depth (D_{act}), the height of sheet pile (D_{all}), and force in anchor are calculated:

$$D = L_3 + L_4 \quad (15)$$
$$D_{act} = 1.3D \quad (16)$$
$$D_{all} = L_1 + L_2 + D_{act} \quad (17)$$
$$F_{anchor} = F - 0.5\gamma_{eff}\left(K_p - K_a\right)L_4^2 \quad (18)$$

The distance of zero shear plane (Z_0), maximum moment (M_{max}), and section modulus (S) are obtained by the following equations:

$$Z_0 = \frac{1}{K_a\gamma_{eff}}\left[-P_1 + \sqrt{P_1^2 - 2(K_a\gamma_{eff})(0.5P_1h_1 - F_{anchor})}\right] \quad (19)$$
$$M_{\max} = \left(-P_1\frac{L_1}{2}\right)\left(Z_0 + \frac{L_1}{3}\right)F_{anchor}\left(Z_0 + h_2\right) - \left(\frac{P_1}{2}\right)Z_0^2 - \left(\frac{K_a\gamma_{eff}}{6}\right)Z_0^3 \quad (20)$$

$$S = \frac{M_{\max}}{\sigma_{all}}; \sigma_{all} = 210 \times 10^3 \tag{21}$$

The parameters in with surcharge condition are calculated based on the following equations (US-Army, 1994 & Das. B.M, 2016).

$$P_1 = K_a q; q = 75kPa \tag{22}$$

$$P_2 = K_a \gamma_{eff} H \tag{23}$$

$$P_3 = K_a \gamma_{eff} D \tag{24}$$

$$P_4 = -K_p \gamma_{eff} H \tag{25}$$

$$F_1 = P_1 H \tag{26}$$

$$F_2 = 0.5 P_2 H \tag{27}$$

$$F_3 = (P_1 + P_2) D \tag{28}$$

$$F_4 = 0.5 P_3 D \tag{29}$$

$$F_5 = 0.5 P_4 D \tag{30}$$

$$\left[(H-D) + \frac{2D}{3}\right] F_4 + \left[(H-d) + \frac{D}{2}\right] F_3 + \left[\frac{2}{3} H - d\right] F_2 + \left[\frac{1}{2} H - d\right] F_1 - \left[(H-d) + \frac{2}{3} D\right] F_5 = 0 \tag{31}$$

$$L = H + 1.3D \tag{32}$$

$$F = \sum_{i=1}^{4} F_i \tag{33}$$

$$F_{fos} = 1.5F \tag{34}$$

Since there are piles and foundation in soil masses, the result of first case (with surcharge condition) is used in numerical method.

Numerical Simulation

The numerical simulation for steel sheet pile is done by using finite element method. The Properties of steel sheet piles and anchor bolt are illustrated in Table 2 and 3. In addition to modeling the soil, pile, foundation, abutment and surcharge due to embankment and live load is considered in numerical modeling. Figure 3 shows the boundary condition and meshing in numerical modeling.

Table 2: Properties of steel sheet piles

Steel type	Dimension	Sectional Area	Moment of inertia	Section Modulus
--	thickness (mm)	Cm^2/m	Cm^4/m	Cm^3/m
ASTM A-328	13.1	186.0	22,800	1,520

Table 3: Properties of anchor bolt

Type	Dimension	Sectional Area	Yield strength	Ultimate Force
--	Diameter (mm)	mm^2/m	f_y (MPa)	(kN)
AIII	32	804	400	320

The numerical situation is performed in three condition: static, earthquake and, adding water level conditions. The deflection of sheet pile, moment resulted in anchored, and safety factor in earthquake condition are shown in Figure 4 to 6. The safety factor in the final step is illustrated in Table 4 for static and earthquake conditions. Based on the figures and Table 4, the safety factors are more than allowable factors and so the model is stable.

Figure 7 is obtained by adding water. The water to the right of the wall will exert a hydrostatic force on the wall and foundation soil. Hydrostatic force on the wall reduces the moment and deformation.

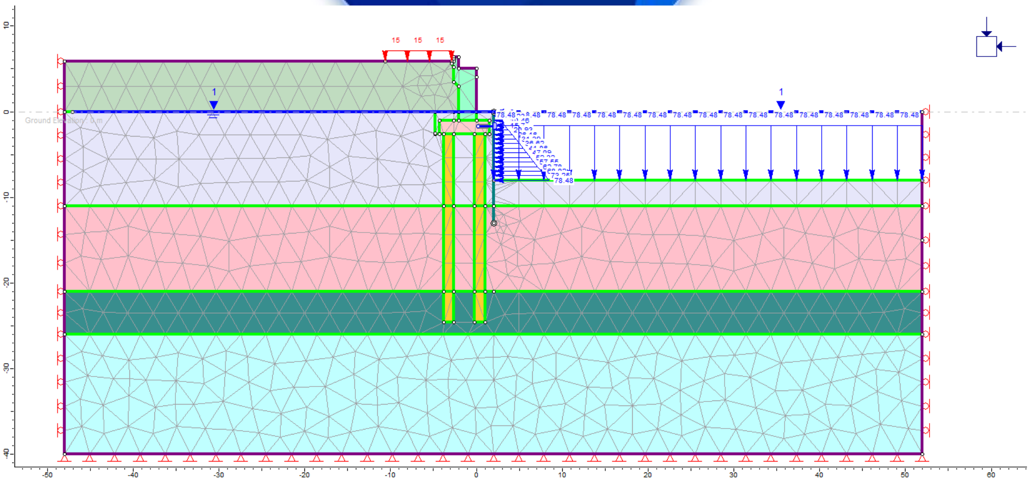

Figure 3: Numerical model of the Abutment and sheet pile

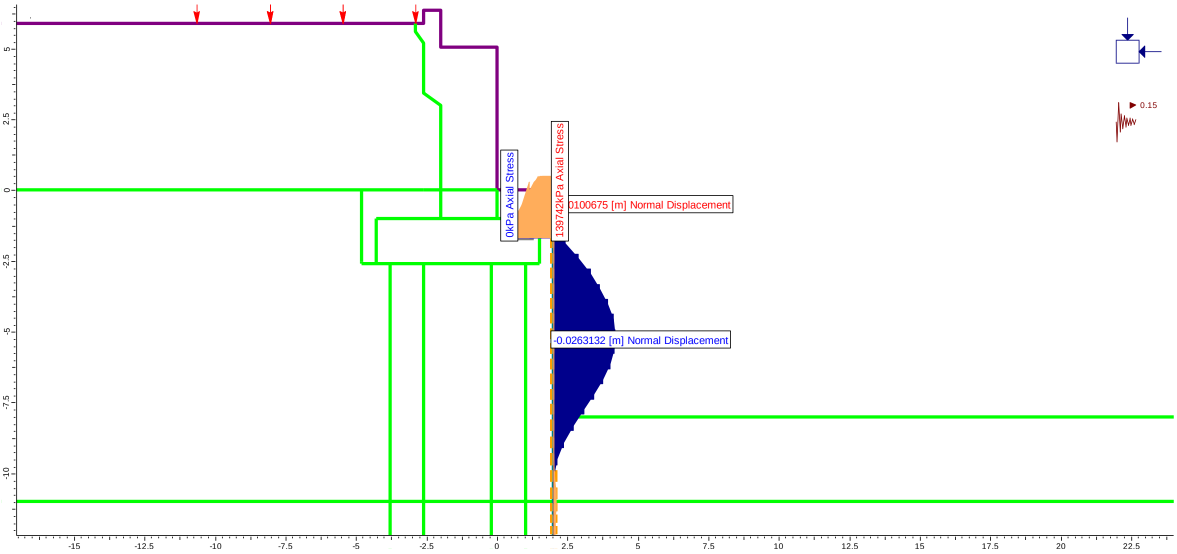

Figure 4: Deflection of sheet pile and stress resulted in anchored

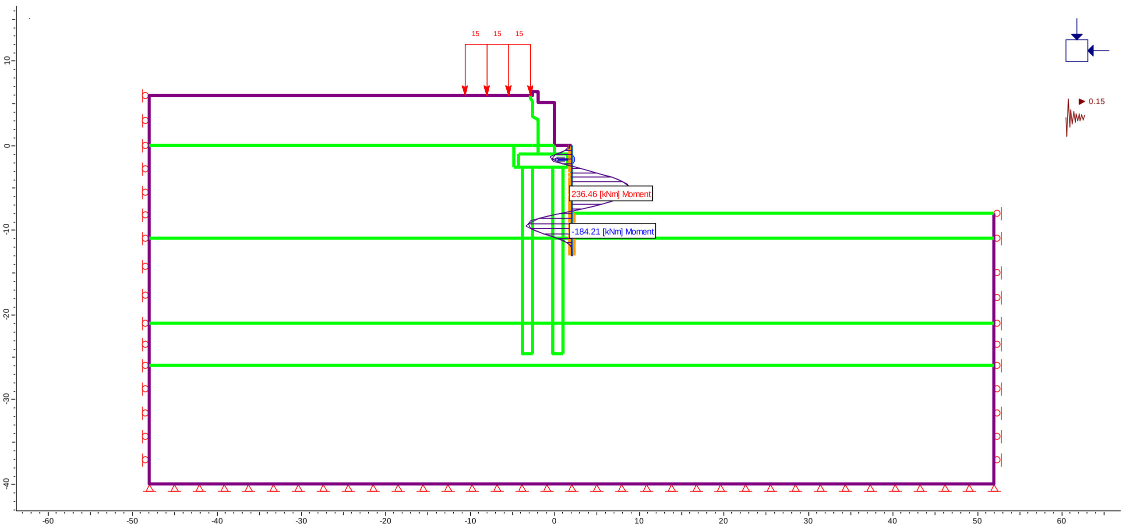

Figure 5: Moment resulted from Numerical model of sheet pile by earthquake analysis

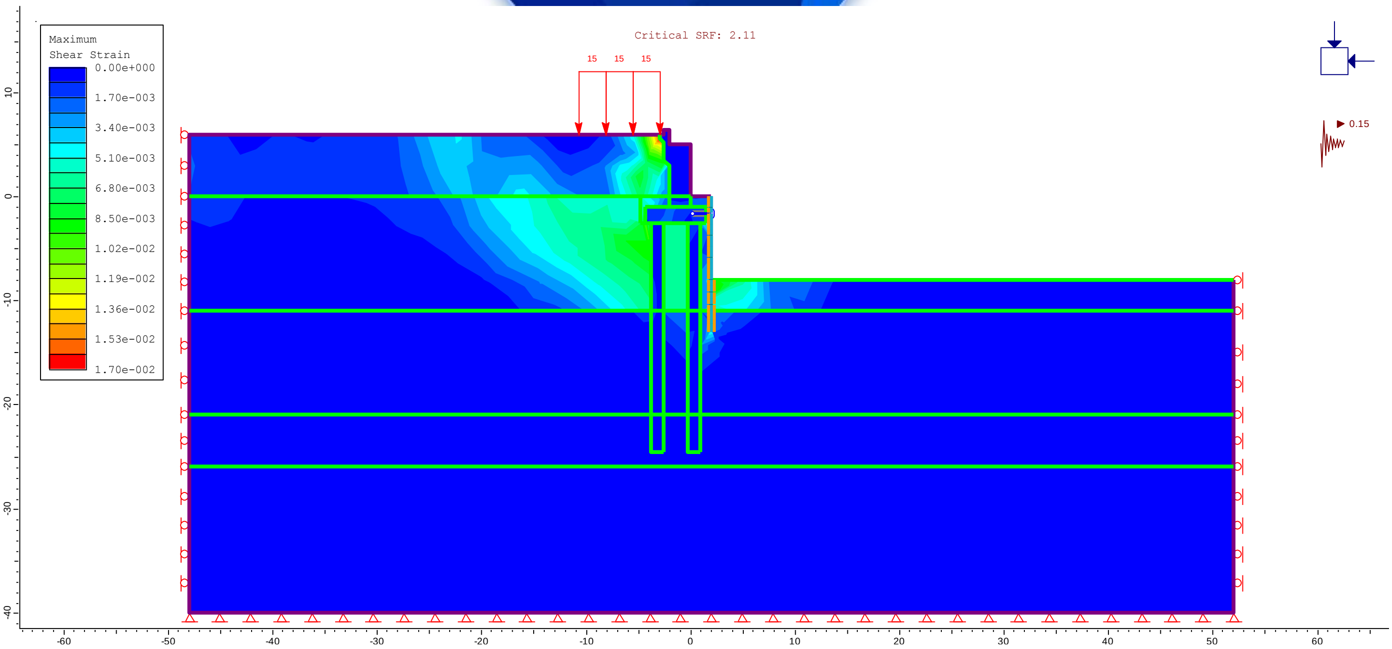

Figure 6: Factor of safety resulted in Earthquake modeling

Table 4: factor of safety for static and earthquake conditions

	Static	Earthquake
Allowable	1.5	1.1
Numerical Modeling	3.34	2.11

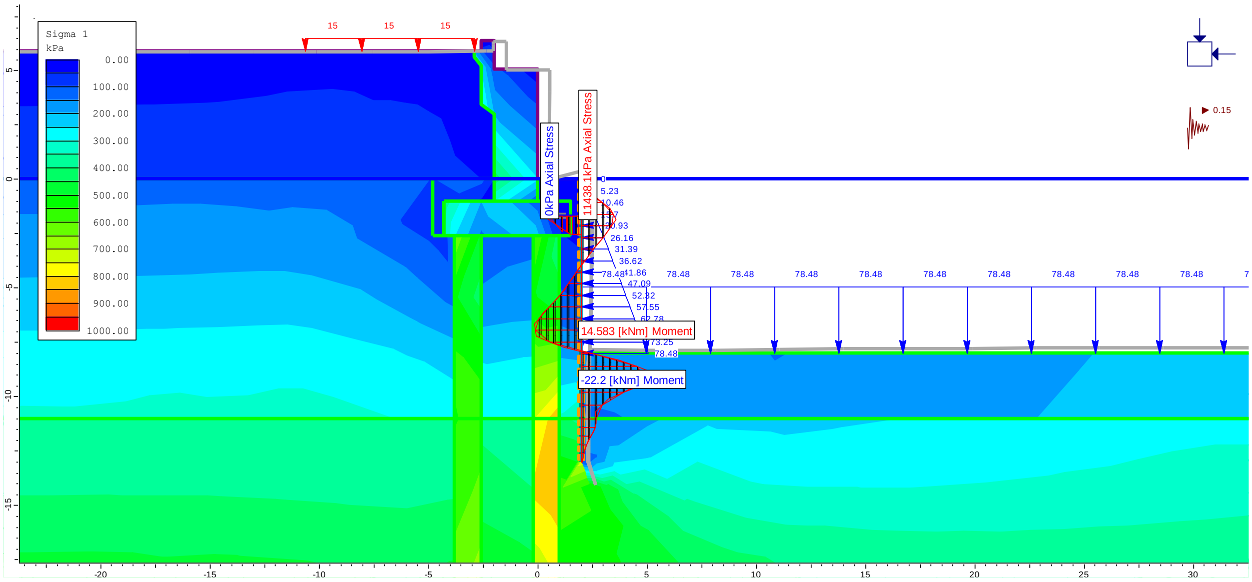

Figure 7: Moment resulted in sheet pile stress resulted in anchored in terms of water level rise

Conclusions

In this paper two classical and numerical methods used for designing sheet pile in Tuti-Bahri bridge. Because section modulus of steel sheet pile is equal to $1.52\times10^{-3}m^3/m$ and maximum moment is obtained 237 kN.m, therefore:

$$F = \frac{M}{S} = \frac{2.37*10^{+3}}{1.52*10^{-3}} = 155MPa < 240MPA$$

Maximum axial stress in both anchors calculated 237 MPa, and it is less than the allowable stress in tension (0.6 Fy) 240 MPa. Nevertheless, the results showed that the sheet pile is stable in all conditions. The properties of steel pile and steel anchor are suggested in Table 5 by considering the classical and numerical results.

Table 5: Results of classical and numerical sheet pile design method

Scour depth		8 m
Properties of steel sheet piles	Steel type	ASTM A-328
	Lenght	13 m
	thickness	13.1 mm
	Sectional Area	186.0 cm^2/m
	Moment of inertia	22,800 cm^4/m
	Section Modulus	1,520 cm^3/m
Properties of steel anchor	Steel type	AIII
	Lenght	26 m
	Spacing	1 m
	Diameter	32 mm
	Sectional Area	804 cm^2/m
	Yield strength	400 MPa
	Ultimate Force	320 kN

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