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Design of a Mechanically Stabilized Earth Wall with Geotextile Reinforcement in Accordance with the Federal Highway Administration Standard

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Abstract*—Geotextile is a geosynthetic constructed for embankment functioning as reinforcement to support tension force from the loading design and decrease the failure potential of embankments. In accordance with the Federal Highway Administration (FHWA) standard, geotextiles are designed under static and dynamic loading on a 7.5 m-high earth wall at Pondok Hijau, Bandung. The reinforced earth wall is known as a mechanically stabilized earth wall. The FHWA design calculation uses the simplified coherent gravity method, while the final analysis is based on the limit equilibrium and finite element methods. The FHWA calculation produces a preliminary design of a 6.5 m-long geotextile with 200 kN/m ultimate tensile strength placed at every 30 cm at the first layer, 50 cm from the second to the seventh layer, and 30 cm from the eighth to the twenty-first layer. The maximum horizontal deformations of the geotextile because of static and dynamic loading are 2.94 and 4.6 cm, respectively. The wall itself also deforms by as much as 5.07 and 7.93 cm owing to static loading and dynamic loading, respectively. The allowable deformation of the geotextile and the wall are 27.3 and 10 cm, respectively. Hence, the preliminary design is valid according to the deformation requirements.

***Keywords*—geotextile, Federal Highway Administration, mechanically stabilized earth wall, stability, deformation**

I. Introduction

Pondok Hijau Residence was established by constructing an embankment as an additional terrain. The embankment itself is categorized as an earth wall as its face batter is 90° (vertical wall) with 7.5 m height [1]. Similar to any other earth wall, the existence of lateral soil pressure inside the soil component makes the embankment unstable. Moreover, the steeper the face batter, the greater the chance the earth wall will fail, especially because it is in a total stand-up position.

Designing cantilever walls is an acceptable yet highly conservative idea. However, along with the times, more alternatives to soil resistance material than gravity or cantilever walls have been adopted. One of them is geotextile, a sheet-shaped polymer material made to support tension forces. Geotextile application inside a backfill increases the stability of earth walls. This concept of collapse prevention differs from those of conventional walls, which act as resistance structures rather than stabilizers. The earth wall installed with a support element is known as a mechanically stabilized earth wall (MSEW). Using the Federal Highway Administration (FHWA) standard, one of the most trusted and commonly referred international design standards, this study seeks to design a geotextile as earth wall reinforcement and verify the stabilization function of the design appliance.

II. Literature Review

A. Geotextiles

Geotextile is a sheet-shaped product made of polymeric material that is used in soil, rocks, or other geotechnical materials part of projects, structures, or other systems related to civil construction [2]. The sheets are a combination of filament yarns made from a polymer material. Geotextile is a permeable geosynthetic. The main polymer materials that form a geotextile include polypropylene, polyester, and polyethylene [1].

The two common types of geotextiles are woven and non-woven geotextiles. The difference between these types is their manufacturing process. Woven geotextiles are produced by weaving filament yarns, which is the conventional method. Conversely, non-woven geotextiles are produced in a modern way, with filament yarns fused using a heat machine. Non-woven geotextiles have less tensile strength compared to their woven counterparts and mostly function only for filter and drainage, whereas geotextiles function as reinforcement. Woven geotextiles that are labeled for reinforcement function are characterized by high elasticity modulus and insignificant deformation as the amount of loading increases [3]. This account is proven by the experiment result depicted in Fig. 1.

B. Earth Pressure

Each soil element in a certain depth of backfill bears pressure identical to the hydrostatic pressure yielded by water. However, unlike hydrostatic pressure, earth pressure is not the same in the horizontal and vertical directions [4].

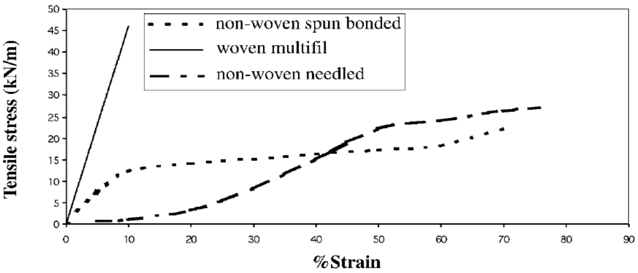

Fig. 1. Typical and Schematical Geotextile Strain-Stress Curves [5]

Therefore, a coefficient was created as a ratio of the horizontal and vertical pressures, designated as the at-rest pressure coefficient (K_o). At-rest pressure is known as a steady soil condition without any additional external force. In other words, the only pressure subjected to the soil component is earth pressure itself. When additional loading occurs, however, the soil component behaves in particular ways. If the loading develops tension force, then the horizontal pressure decreases and so does the pressure coefficient. The horizontal pressure and coefficient value continue to drop until they reach their minimum values. These circumstances are called the active condition, and the earth pressure and pressure coefficient are denoted as the active earth pressure and active pressure coefficient (K_a), respectively. Conversely, the passive condition signifies the presence of a compression force applied on the soil mass. Therefore, both horizontal pressure and coefficient value increase to their peak values and turn into passive earth pressure and passive pressure coefficient (K_p), respectively.

C. Earth Resistance Structure

In accordance with the design of an earth resistance structure, an analysis is conducted on both active and passive conditions to allow for backfill deformation and on the structure itself. The dissimilarity between active and passive conditions is the deformation direction itself. Specifically, the active condition assumes that the resistance structure moves away from the backfill, whereas the passive condition tolerates structural displacement heading to the backfill.

With reference to [6], the MSEW is permitted to displace horizontally with a maximum displacement of $\frac{H}{75}$ for flexible reinforcement. Accordingly, the analysis uses an active condition with limited displacement. Based on Rankine's theory, the active condition has a failure plane as an effect of the active earth pressure (Fig. 2). For a backfill with a vertical wall and horizontal slope, the value of K_a can be determined by Equation (1).

$$K_a = \tan^2\left(45° - \frac{\phi}{2}\right) \quad (1)$$

D. Soil Reinforcement

Several theories exist regarding mechanical soil reinforcement. The most-well known theory is that soil reinforcement has the same behavior as steel reinforcement in concrete. Soil and concrete can only restrain a large compressive force. Therefore, reinforcement is needed to prevent either soil or concrete from failure in case a large tension force develops. Geotextile is used to sustain the tensile force encountered in soil mass with the polymer yarns as the tensile force accommodator [7].

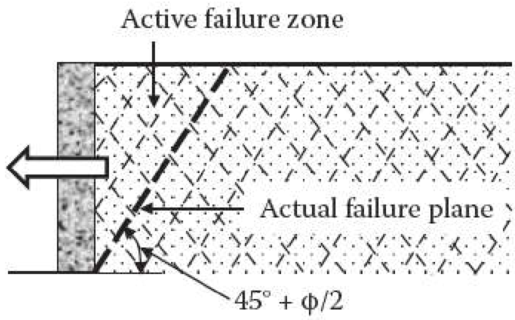

Fig. 2. Potential Failure Plane of an Active Conditioned Backfill [8]

However, the other theorist [9], implied that soil reinforcement adds a cohesive trait to non-cohesive soil. This tendency comes from the physical form of the reinforcement itself, as seen in Fig. 3. Therefore, the anisotropic strain subjected to the soil mass is reduced, and the final strain is similar to the at-rest pressure condition, which was previously found in the active pressure condition. Furthermore, different pressure conditions result in different values of the pressure coefficient, where the at-rest condition is greater than the active condition ($K_a < K_o$). In the same loading condition, the circumference stress imposed on at-rest soil mass becomes greater, so stability of the soil improves, and horizontal deformation is reduced.

Sheet-type reinforcements like geotextiles use friction as a stress distribution from soil to the reinforcement. The friction comes from the interaction between the soil and the reinforcement, wherein the stress distribution occurs. However, the distribution must be limited by the efficiency value to prevent mismodeling because of 100% efficiency, which assumes that the soil and the reinforcement are concerted and have the same failure criterion. The efficiency number is known as the interface or friction coefficient (R-interface), which is applied on the soil friction angle and becomes the geotextile friction angle. This geotextile friction angle must contain soil movement through the friction force. In line with [10], the number of R-interfaces for woven geotextiles among sand ranges at approximately 0.7–0.8.

E. Geotextile on Mechanically Stabilized Earth Wall

Settling the mechanical reinforcement on an earth wall serves to steady soil mass that can be mobilized as a result of the earth lateral pressure effect. In line with [11], the reinforcement will accommodate tension force subjected to soil mass and increase the soil strength so the wall will prop up by itself.

Geotextiles are commonly used in wrap-around-face MSEWs. This type of face is also produced more effortlessly than other facing alternatives by stretching the geotextile sheet and folding it onto the base of the upper layer. Thus, the wall surface will be covered by the wrapped geotextile. Fig. 4 shows a cross-section view of the geotextile and wrapped-around facing placement.

The FHWA is one of the most trustworthy American institutes concerning transportation and traffic engineering regulation guidelines for designing geosynthetics on earth walls. A disadvantage of its standard is that it is suggested only for permanent and critical designs. Nonetheless, the FHWA still prevails for conservative and non-critical designs, as stated in the main standards referred to in this design, namely, FHWA-HI-95-038 and FHWA-NHI-00-043.

III. Design Procedures

The subjected earth wall is located at Pondok Hijau Residence, Bandung, Jawa Barat, next to earlier domiciles. Its height is 7.5 m upright. The overall soil material is assumed to be sand, as the standard requirement of the

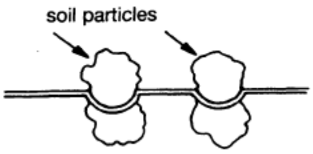

Fig. 3. Representation of Soil Reinforcement [10]

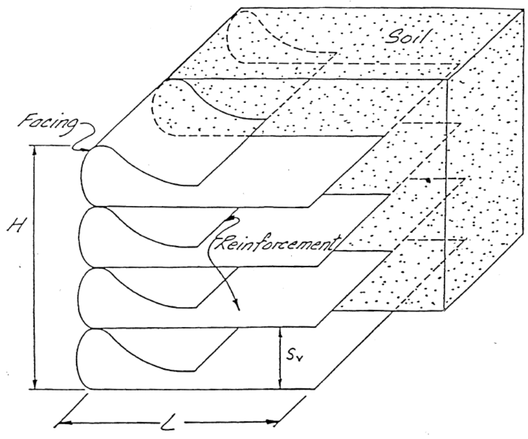

Fig. 4. Illustration of Geotextiles on an Earth Wall [9]

modeled parameter is based on the field test (CPT) specifically carried out on the sand layer modeled in Fig. 5.

Similar to every geotechnical design, both static and dynamic loading must be included. The procedures and equations for analyzing both loading conditions are already covered in [11]. The static load is assumed as the traffic loads, the infinite loads are at 9 kN/m^2 as mentioned in [12], and the dynamic load is based on the peak ground acceleration value at the location. Figure 6 is the MSEW modeled by the FHWA and force illustration to perceive the manual calculation, while Fig. 7 includes additional dynamic loading in the MSEW model. The procedures and formulas for each step can be seen in the FHWA guidelines.

Before the procedures are followed, the preliminary design of the geotextile must be determined as the first design tested in the procedures. The specification that resulted from external stability control is the geotextile's length (L), and the internal stability control involves the ultimate strength (T_u) and geotextile spacings (S_v). Consequently, the actual tensile force developed in each geotextile layer under static loading (T_{max}) must be calculated. Equation (2) is presented to determine the maximum static tensile force.

$$T_{max}=S_v\ \sigma_H \tag{2}$$

where

T_{max} = maximum geotextile static tensile force at the layer ($\frac{kN}{m}$),

σ_H = total earth lateral pressure at the layer, and

S_v = force catchment area $=\frac{1}{2}$ (upward spacing+downward spacing) (m).

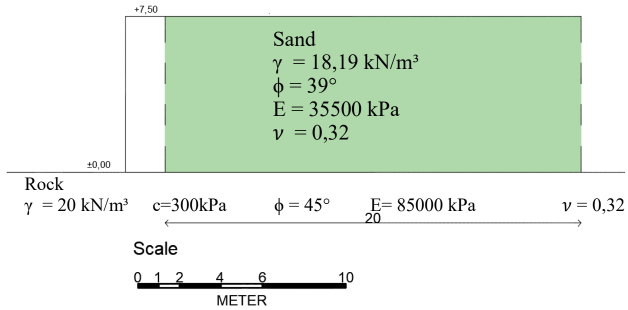

Fig. 5. Soil Stratification Research

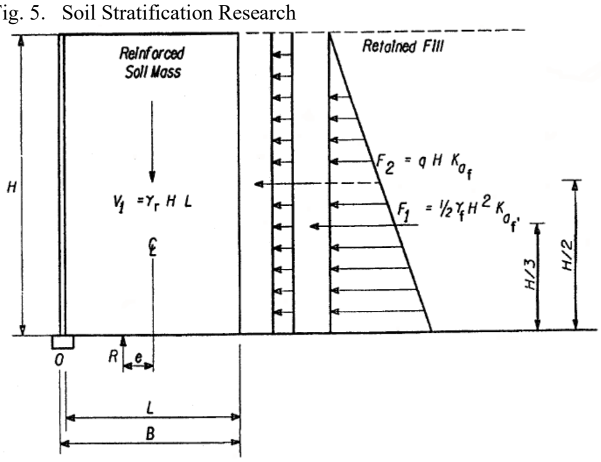

Fig. 6. Model Geometry and Force Distribution of MSWE Under Static Loading [11]

Owing to the environmental condition that probably affects geotextile strength, some reduction factors of the environmental components are applied to define the allowable geotextile strength in the field. The environmental components involve creep, installation damage, and chemical or biological materials that can degrade the geotextile.

IV. Performance Criteria

The MSEW design must consider potential external failures and their factors of safety as follows [1,11]:

1. Force Eccentricity (e)
   The maximum value of e is L/4 for the MSEW constructed in the rock base and L/6 in the soil base.
2. Base Sliding
   The MSEW base layer is the most critical because both embankment and base soil intersect with geotextile so the interface factor must be considered, especially when the base soil has less strength than the embankment soil. The lowest safety factor required for base sliding is 1.5.
3. Overturning
   The reinforced wall must maintain its steadiness at the turning point with at least with 2.5 factors of safety.
4. Bearing Capacity

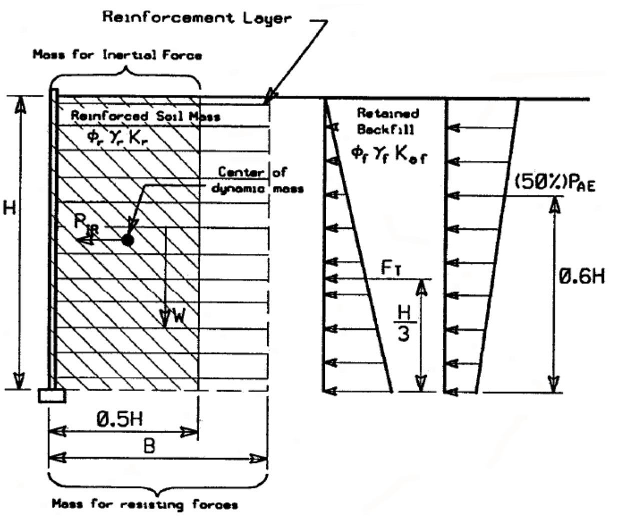

Fig. 7. Model Geometry and Force Distribution of MSWE with Additional Seismic Loading [11]

A minimum 2.0 factor of safety is required for the foundation soil to prevent a large settlement.

5. Global Stability

   Overall external stability analysis must identify a minimum safety factor of 1.3. However, the standard allows for a safety factor of 1.1 owing to dynamic loading.

These pass criteria are only affected by the length of the geotextile itself. Thus, the minimum length of the geotextile is defined as 0.7 H. Conversely, the most important variable in internal stability control is the allowable and ultimate design strength of the geotextile (T_{all} and T_d, respectively). These strength values can be calculated respectively using Equations (3) and (4).

$$T_{all}=\frac{T_{ult}}{RF_{CR}\cdot RF_{ID}\cdot RF_{D}} \quad (3)$$

$$T_d=\frac{T_{all}}{SF} \quad (4)$$

where

T_{ult} = ultimate geotextile tensile strength ($\frac{kN}{m}$),
T_d = design geotextile tensile strength ($\frac{kN}{m}$),
RF_{CR} = creep reduction factor,
RF_{ID} = installation damage reduction factor (1.05–3.0),
RF_D = durability reduction factor due to degradation (1.1 – 2.0), and
SF = safety factor.

To avoid reinforcement breakage and pullout, a geotextile is enforced to capacitate a 150% design load with deformation that is within the product's requirement given in the catalog. In other words, the value of SF is 1.5, and in determining maximum geotextile deformation relevant to the product designation, preliminary sizing must first be designed. However, [13] recommends a 3%–5% elongation of reinforcement in an earth wall. The requirement for maximum global deformation of $\frac{H}{75}$ is already stated above.

V. Results

A. Preliminary Design

For the preliminary design to be verified in overall stability analysis and implicated in the construction stage criteria, numerical analysis is performed using the limit equilibrium method (LEM) and finite element method (FEM). Both methods are chosen as they are frequently used in geotechnical problems. Limit equilibrium analysis is performed using Slide software, and FEM uses PLAXIS 2D software.

The geotextile adopted for the preliminary design is a polyester woven geotextile with 200 kN/m ultimate tensile strength. According to the reduction factor value recommended by the FHWA and the product company, the reduction factor values used in the analysis include RF_{CR}=2, RF_{ID}=1,15, and RF_D=1,1. Thus, the geotextile has allowable and design tensile strengths of 79.05 and 52.7 kN/m, respectively. As for the facing, wrap-around facing is chosen and the spacing range required is 30–50 cm. After several trials were completed, the optimal values were determined to be 6.5 m geotextile in 30 cm spacing for the top layer, 50 cm spacing for the second until the seventh layer, and then 30 cm spacing for the rest of the layers. Note that the minimum length of the geotextile required is 0.7 × 7.5 m = 5.425 m. The details of the preliminary design in the MSEW are shown in Fig. 8.

The allowable tensile strength represents the geotextile ultimate tensile strength in the field (as the environment and durability factors are included), and so the maximum geotextile deformation can be determined. The percentage of allowable tensile strength to ultimate tensile strength is 39.53%. The product's strain–stress curve (Fig. 9) indicates that for 39,53%T_u accession of field tensile strength, the maximum strain allowed is 4.2%. Therefore, with a 6.5 m length of geotextile, 27.3 cm of deformation is tolerated before the geotextile is presumed to break, and the maximum system deformation is $\frac{H}{75}=\frac{7.5\text{ m}}{75}$ = 10 cm.

In accordance with the FHWA, the lateral earth pressures subjected to the reinforced earth wall are separately calculated between the internal and external sections. Internal earth pressure occurs in the reinforced area whereas external pressure emerges in the soil mass right behind the reinforcement. However, as the case geometry appears to be a vertical wall with a horizontal backslope, the values of both types of earth pressure are equal.

B. External Stability

The results of the manual calculation of external stability factors are obtained through adopting the external stability formulation described in the FHWA (Table I). By contrast, Plaxis 2D assumes a drained condition in the analysis as the backfill consists of sand. As a result of the finite element analysis, the safety factor for MSEW after full construction is 1.89. The failure planes based on both methods are displayed in Fig. 10. The findings for the external stability alongside the design safety verification are presented in Table I.

C. Internal Stability

To confirm the safety of internal stability, the maximum tensile force that occurred in each geotextile layer must be limited to the design tensile strength. Note that the maximum tensile force is calculated only under static loading. The maximum tensile force distribution can be seen in Fig. 11.

The greatest tensile force in the amount of 18,48 $\frac{kN}{m}$ takes place in layer 20 (Fig. 11), although it has not reached T_d. Given this value of maximum tensile force, the additional

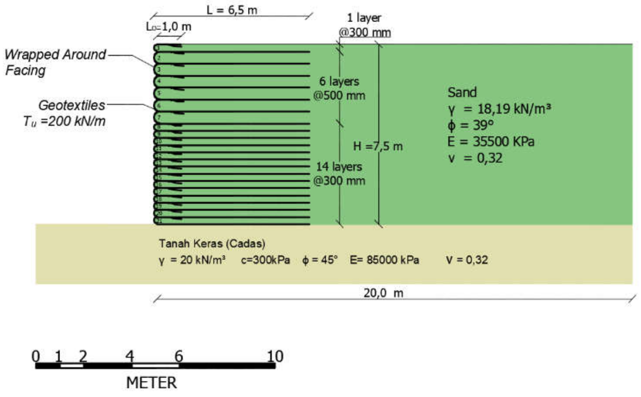

Fig. 8. MSWE Design

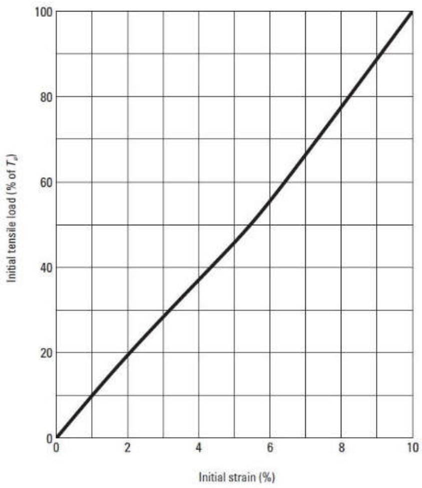

Fig. 9. Initial Tensile Load–Strain Master Curve for Polyester Geotextiles [14]

geotextile length behind the failure area (L_e) can be determined. The calculation indicates that an additional 1 m length is necessary. Then, the total length of the geotextile for each layer is 6.5 m, which is formed by adding 5.5 m requisite length (roundup from 5.425 m) to the 1 m additional length. This designed length reinforcement eventually passes through Rankine's failure plane as the preliminary requirement based on the FHWA.

To control the actual maximum tensile force that occurs, finite element analysis is added to show the tensile force and deformation of the geotextile involved in the construction stage. The geotextile deformation from the results is assumed to be represented by a horizontal displacement. From Plaxis 2D, the geotextile has a maximum force and horizontal displacement of 8.3 kN/m and 2.94 cm, respectively, values that are much lower than the allowable values. Thus, the output parameters already fulfill the performance criteria. Corresponding to the geotextile outputs, the overall system deformation also meets the criteria, where 5.07 cm MSEW deformation occurs while the maximum deformation permitted is 10 cm.

D. Dynamic Stability

The dynamic loading used in this analysis is earthquake loading based on peak ground acceleration (PGA) on site. Indonesia's Residence Research and Development Center report that the value of the PGA on site is 0.593.

TABLE I. EXTERNAL STABILITY VERIFICATION FOR LOCAL AND GLOBAL COLLAPSE UNDER STATIC LOADING

No.	Collapse Type	Stability Variable	Design Safety Value	Safety Value Limit	Status
1	Force Eccentricity	e (m)	0.36 m	Max.1.63	Safe
2	Overturning	SF	8.5	Min. 2.0	Safe
3	Base Sliding	SF	3.67	Min. 1.5	Safe
4	Bearing Capacity	SF	431.65	Min. 2.5	Safe
5	Global Stability (LEM)	SF	2.71	Min. 1.3	Safe
6	Global Stability (FEM)	SF	1.89	Min. 1.3	Safe

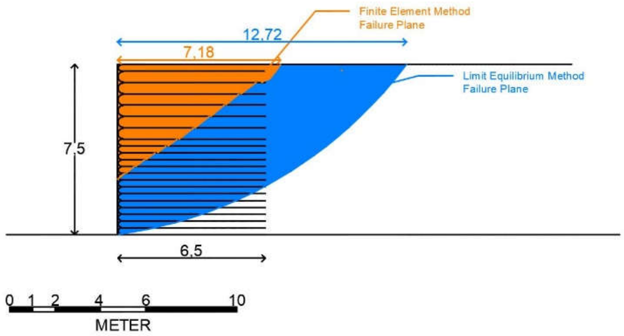

Fig. 10.Static Failure Plane of MSWE Design Based on LEM and FEM

As a result, the PGA used for the analysis is reduced to 0.508. The analysis of dynamic stability is also separated into internal dynamic stability and external dynamic stability evaluations.

In external stability calculation, both reinforced and unreinforced sections are accelerated as a consequence of seismic loading. P_{IR} is known as the soil inertia force that appears in the reinforced section of soil mass, while P_{AE} develops in the backfill area (Fig. 7). Therefore, external safety factors must be calculated again, especially for factors that are most affected by the dynamic forces. The safety factors must meet a minimum 75% of static safety factors and a maximum $\frac{L}{3}$ of eccentricity, which means values of 1.125 for the sliding safety factor, 1.5 for the overturning safety factor, and 2.32 m maximum for eccentricity. With the same calculation procedures, the analysis outputs are as follows: the safety factors of sliding and overturning are 1.52 and 1.76, respectively, and 1.85 m eccentricity occurs in the system.

Unlike local stability, global stability must meet a safety factor of 1.1 minimum. The results of limit equilibrium analysis with 0.508 PGA is 1.21, and the FEM is 1.6. The failure plane results are displayed in Fig. 12. The tensile forces that developed in the geotextile layer also increase due to dynamic charge. The dynamic stresses (T_{md}) that appear in each layer must be substituted with static stresses (T_{max}) to produce the total stress of the geotextile. These combined stresses are not allowed to surpass the design tensile strength of the geotextile. The analysis states the maximum combined stress of the geotextile is 25.87 kN/m, a value lower than the designed tensile strength. Likewise, Plaxis 2D delivers a maximum geotextile force of 13.2 kN/m, a value much lower than the calculation output.

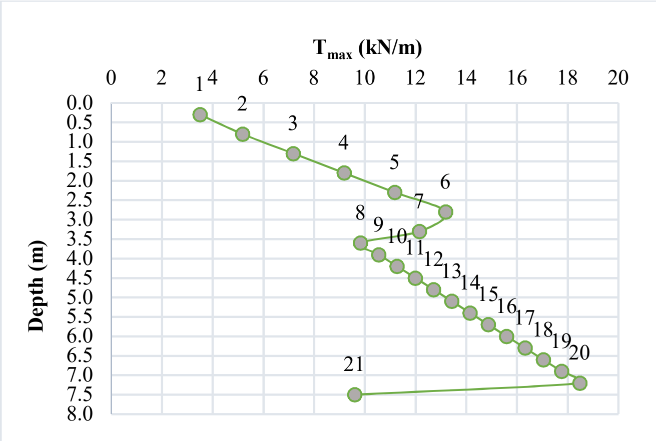

Fig. 11. Maximum Static Tensile Force (T_{max}) Distribution Alongside the Geotextile Layer

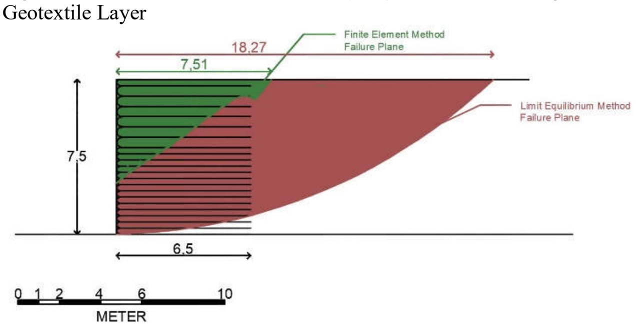

Fig. 12. Dynamic Failure Plane of MSWE Design Based on LEM and FEM

Furthermore, material failure potentials arise as the effect of accelerated reinforced soil. As in the geotextile, the possibility of breakage emerges when the dynamic stresses are nearly the same as the static stresses, particularly in the top layer. Accordingly, the combined stress on the layer is doubled. The chances of the geotextile being pulled out must also be considered. The breakage control parameter is the minimum ultimate tensile strength of the geotextile (T_{umin}) because the geotextile will become brittle after reaching its ultimate strength. Furthermore, the geotextile's pullout capacity must be greater than the pullout force that occurs. The pullout force is represented by combined stress. These failure criteria are also considered in the dynamic analysis.

TABLE II. EXTERNAL STABILITY VERIFICATION FOR LOCAL AND GLOBAL COLLAPSE UNDER DYNAMIC LOADING

No.	Collapse Type	Stability Variable	Design Safety Value	Safety Value Limit	Status
1	Force Eccentricity	e (m)	1.85	Max. 2.32	Safe
2	Overturning	SF	1.76	Min. 1.5	Safe
3	Base Sliding	SF	1.52	Min. 1.125	Safe
4	Global Stability (LEM)	SF	1.21	Min. 1.1	Safe
5	Global Stability (FEM)	SF	1.6	Min. 1.1	Safe

In relation to deformation, both system and geotextile deformations have not surpassed the maximum allowable values. The respective deformations of the MSEW and geotextile are 7.93 and 4.6 cm. Thus, for external and internal stability due to static and dynamic loading, all performance criteria are fully covered.

VI. CONCLUSION

The undertaken analysis obtains a final design suitable for an MSEW at Pondok Hijau Residence, Bandung. The geotextiles laid out in this design are 6.5 m polyester geotextiles with 200 kN/m ultimate strength, installed in all layers with 30 cm spacing, except for the second to seventh layers which use 50 cm spacing. Therefore, a simple, conservative, yet effortless construction design of stabilized earth wall is established alternatively with geotextile reinforcement.

Although the safety and deformation preconditions of the system are nearly fulfilled, the geotextile's strength capacity is not fully augmented according to both analyses. In other words, the external stability of the wall is already fully reached before the internal stability is achieved. Furthermore, the FHWA standard does not accommodate maximum deformation of the reinforced earth wall, and this gap induces entanglement with other standards, an outcome that is certainly not thoroughly pertained to with the FHWA itself. Therefore, deeper research and development of the FHWA standard are needed, along with the distinction of the relevance of stability conditions.

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