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Analysis and Design of a High-Risk Tiered Retaining Wall Using a Geosynthetic Reinforcement System

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ABSTRACT Infrastructure development in Indonesia often faces rugged terrain and high seismicity, requiring advanced geotechnical solutions. One of the challenges lies in ensuring that an embankment can effectively withstand heavy loading conditions. Mechanically stabilized earth (MSE) walls provide a safe and efficient option to address these RSS with a total height of 26.95 meters based on a previous project. The structure is designed to withstand a large static surcharge load (up to 375 kPa) and a seismic load with a peak horizontal ground acceleration (kh) of 0.225g. The method employed is a limit equilibrium stability analysis using Janbu's simplified method of slices for non-circular failure surfaces, referring to the SNI 8460:2017 standard, and utilizing TensarSlope software. The selected system is the SierraScape System, which combines high-strength uniaxial geogrid primary reinforcement with a flexible welded wire for facing. The analysis results show that the retaining wall design meets the required factors of safety for both static (FS = 1.301 > 1.300) and seismic (FS = 1.163 > 1.100) conditions. In conclusion, this case study demonstrates that the application of modern geosynthetic reinforcement systems is a reliable and effective solution for addressing geotechnical challenges in high-risk projects in Indonesia, contributing a design reference for similar conditions.

KEYWORDS MSE Wall; High Risk Tiered; Heavy Loading Conditions, Reinforced Retaining Structure; Geosynthetic Reinforcements

1 INTRODUCTION

The need for geotechnical investigations becomes especially significant in harsh environments such as rugged mountain areas (Adesina et al., 2024). Land limitations and the need for spatial optimization often involve the construction of high and steep retaining structures. Furthermore, one of the challenges lies in ensuring that an embankment can effectively withstand heavy loading conditions. In addition, a large portion of Indonesia is located in an active seismic zone, making seismic loading a crucial parameter in every design (PuSGeN, 2017).

Mechanically Stabilized Earth (MSE) walls, or geosynthetic-reinforced retaining walls, have gained popularity as they offer reduced site preparation needs and lower costs compared to conventional retaining systems (Hossain et al., 2012). MSE wall systems also produce lower environmental impacts compared to gravity and cantilever wall types (Damians et al., 2017). According to a study in Turkey by Erten & Güler (2016), considering average transport distance for materials, MSE walls are expected to generate 69% less carbon for 3 m walls, 75% less for 4 m walls, and 80% less for 5 m walls. In addition to the economic and environmental benefits, MSE walls offer improved stability as their working principles involve creating soil–reinforcement composite that can withstand tensile forces while keeping the soil body stable. The stability is further improved by the mechanical connections that secure the geosynthetic to the facing (Han et al., 2018).

Various studies have demonstrated the reliability of MSE Wall systems under different loading conditions, from zero or low-level surcharge loads on top of the MSE Wall to very high surcharge of 100 kPa (Konnur et al., 2019; Sayed et al., 2022; Bohrer & Vidal, 2024; Raouf & Bahloul, 2024; Hammad et al., 2025). However, all the previous studies focused on non-tiered MSE walls. For extreme height with massive surcharge loads in high seismic zones, tiered MSE walls often become necessary. Tiered MSE walls require in-depth analysis, and there is a limited publication regarding comprehensive design analyses for such specific configurations in Indonesia.

This paper presents a successful design of 27 m high three-tiered MSE walls used to support heavy industrial facilities. The paper includes the design methodology, parameters used, in addition to the stability analysis results. This paper aims to provide a detailed technical reference for practitioners and academicians in designing similar cases to achieve safe and efficient structures.

2 METHODOLOGY

The following sub-sections outline the step-by-step procedure of this study, beginning with site conditions description, MSE wall layout, information on the soil properties, geogrid, and loading condition, followed by numerical modeling and internal stability analysis.

2.1 Site Conditions

This project is located in a mining area, a previously cleared site, and some boreholes revealed that the subsurface conditions consist mainly of stiff to very stiff silty clay and very dense gravelly sand/silty sand/silt gravel. Beneath these soils, moderately weathered to fresh volcanic rock (andesitic tuff) was encountered, with the strength varying from medium to ‘high. The upper 3m of this bedrock was highly fractured and contained calcite-filled seams and joints. Moreover, groundwater could not be identified during drilling due to the use of drilling fluids for cutting removal.

The simplified existing ground conditions are presented in Figure 1. The lowest layer, rock’, represents moderately weathered rock. This is overlain by a gravelly sand layer. Above the gravelly sand, a structural fill layer is placed after the clay layer was excavated. This structural fill consists of well-graded compacted granular material with a maximum particle size of 53 mm, while the general rock fill layer encompasses compacted granular material with a maximum particle size of 300 mm and little to no fines. Subsequently, the MSE wall was constructed on top of the structural fill layer.

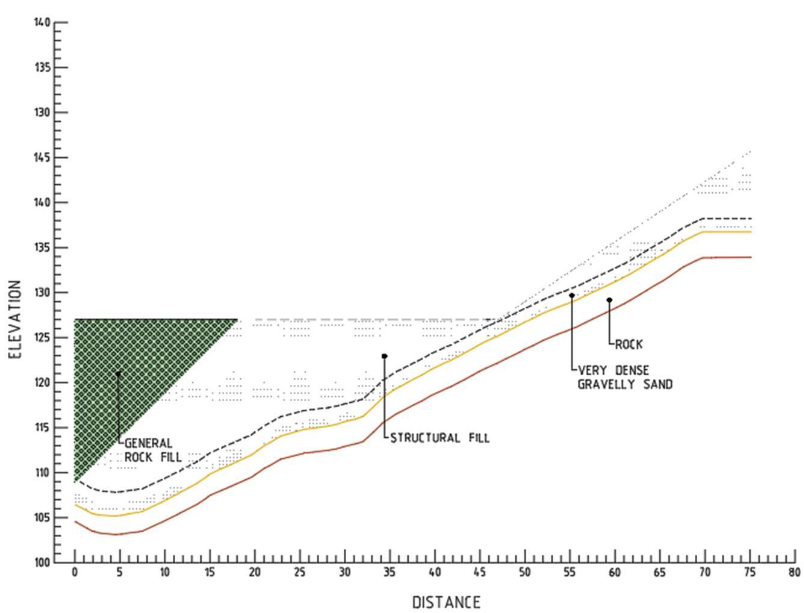

Figure 1. Typical cross-section of existing ground condition prior to the retaining wall construction

2.2 MSE Wall Configuration

For this case study, a three-tiered SierraScape Retaining Wall System with a total height of 26.95 meters was designed. The SierraScape Retaining Wall System, trademarked by Tensar, consists of a welded wire form (WWF) facing and uniaxial HDPE geogrid reinforcement, connected together by a locking tail strut. Figure 2 shows the schematic diagram of SierraScape Retaining Wall System.

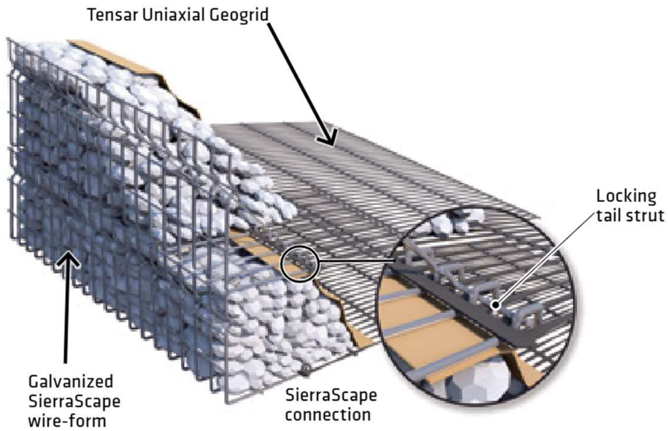

Figure 2. Schematic diagram of SierraScape Retaining Wall System

Figure 3 and 4 show the MSE wall layout and the cross-section of the design, respectively. As shown in Figure 3, section CH 103.400 was taken for analysis as it represents the critical section with the greatest height along the 141.75 m section. Based on the cross-section, each individual tier has a slope angle of 85°, while the backstep between the first tier and second tier, and second tier and third tier are 4.5 m and 5.5 m, respectively. The first tier is 8.4 m high including a 1.4 m embedment, while the second and third tier are 9.1 m and 10.15 m high, respectively, with 0.35 m embedment. The first tier is reinforced with 25 m long Tensar RE580 geogrid, while the second tier is reinforced with 22 m long Tensar RE580 geogrid and the third tier is reinforced with 17 m long Tensar RE570 and RE540 geogrids.

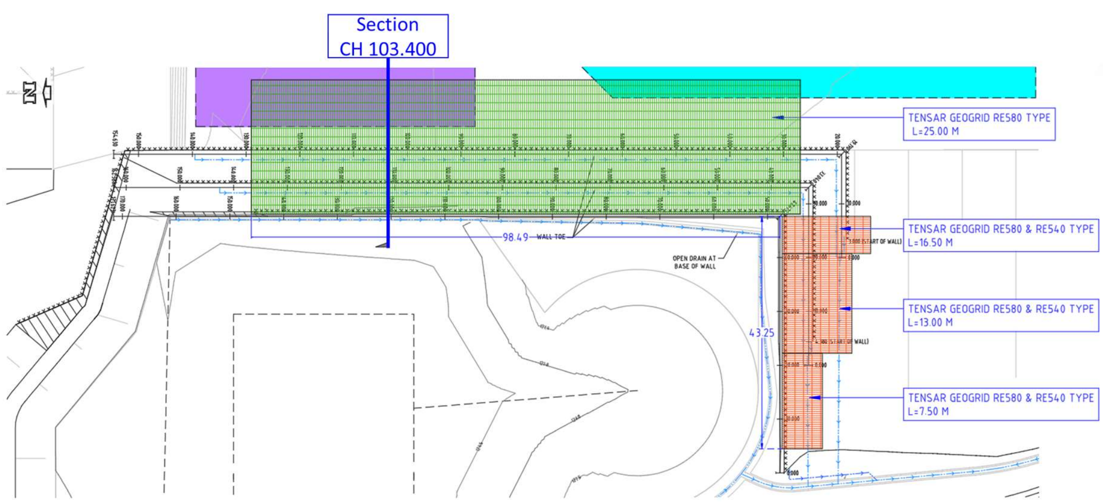

Figure 3. SierraScape Retaining Wall System layout

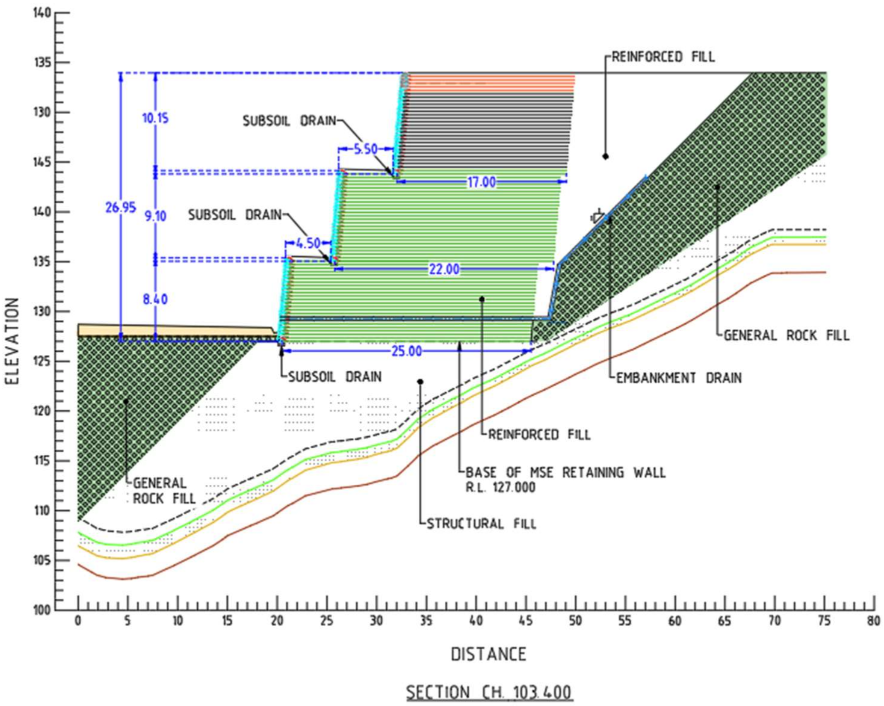

Figure 4. Cross-section of SierraScape Retaining Wall System (Section CH 103.400)

2.3 Soil Material Properties

The existing structural fill is assumed to be adequately compacted to withstand the MSE wall on top of it. Therefore, the very dense material and rock layers beneath the structural layer are not modeled (see Figure 5). The material parameters used in the analysis were obtained from the soil investigation report – the exact values were given by the clients – and technical material specifications of the project, with the details as shown in Table 1.

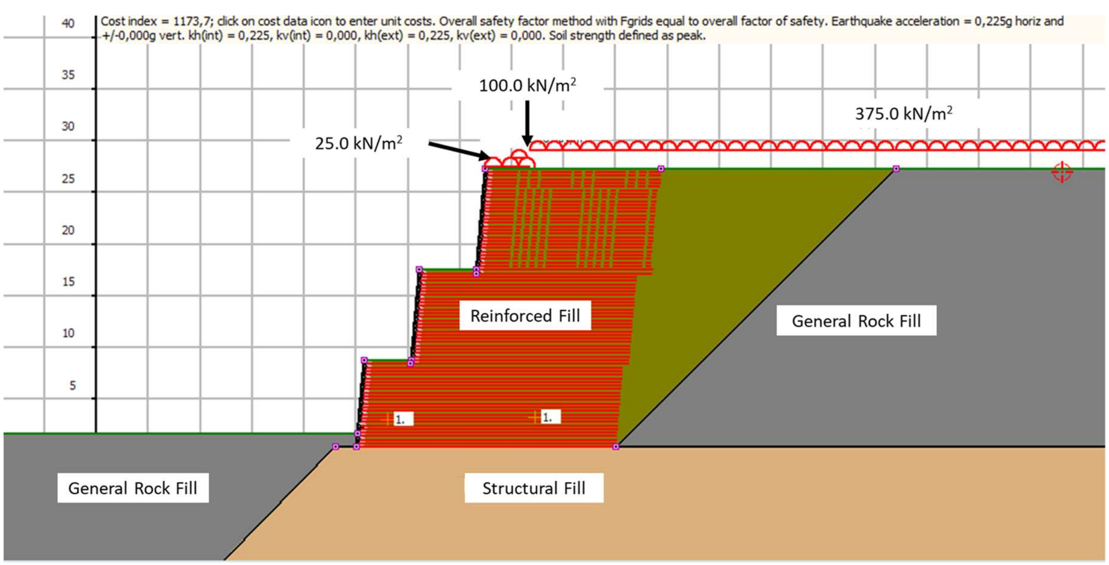

Figure 5. MSE wall model using SierraScape Retaining Wall System

Table 1. Soil input properties

Soil type	Drained / undrained	c' (kN/m^2)	φ' (°)	γ_{bulk} (kN/m^3)
Reinforced Fill	Drained	0.0	40.0	20.0
Structural Fill	Drained	0.0	40.0	20.0
General Rock Fill	Drained	0.0	35.0	20.0

Note that c' is the effective cohesion of the soil, φ' is the friction angle, and γ_{bulk} is the bulk unit weight.

2.4 Loading Information

The surcharge loads are very high as the MSE wall is required to accommodate operation of the industrial facilities. From the edge of MSE wall to 4.3 m behind it, a 25 kPa dead load was applied to model the bund wall weight. A 100 kPa live load is placed 2.5 m from the edge of the MSE wall, with a length of 1.8 m. Finally, behind the 4.3 m dead load, dead load of 375 kPa is applied. The surcharge configuration can be seen in Figure 2. The seismic loading is derived from the Indonesian National Standards, SNI 9460:2017 (Badan Standardisasi Nasional, 2017). Based on SNI 9460:2017, the site has a relatively high seismic risk with a peak ground acceleration (PGA) of 0.45g. In accordance with the national standard, the peak horizontal acceleration at the ground surface (k_h) is taken as half of the PGA, resulting in a value of 0.225g.

2.5 Analysis Using TensarSlope Software

The analysis was carried out using TensarSlope software, which uses the Limit Equilibrium Method (LEM). This is an in-house software created by Tensar. The software can be used for slope stability analysis, while considering specific wall or slope configuration and consists of additional features to accurately analyze MSE walls or reinforced slopes with Tensar geogrid products. The software can also take into account the long-term design strength (LTDS) of the Tensar geogrid products selected by the user. This value accounts for installation damage, creep, and environmental degradation over the design life. The chosen analysis method was Janbu's simplified method of slices. This method was selected for its ability to model non-circular failure mechanisms, which are more realistic for reinforced soil structures where the failure plane tends to follow the weakest path formed by the interaction between the soil and reinforcement layers.

2.6 Geogrid Reinforcement Properties

The Tensar geogrids have been tested in accordance to ISO/TR 20432, which takes into account creep, creep rupture, installation damage, weathering, chemical degradation, and biological degradation (Dobie, 2016). These tests are used to determine the long-term design strength of a geogrid. For this case study, the long-term design strength is set for 120 years. Table 2 presents the 120-year-long-term tensile strengths for Tensar geogrid of types RE540, 570, and 580, retrieved from Tensar technical note "TN/RE500spec30°C". In this analysis, however, a design life of 30 years was adopted, as the strength for this year setup is determined automatically by the software.

Table 2. Input parameter for Tensar RE500Geogrid

Properties	Units	Tensar RE500 geogrid series		
		RE540	RE570	RE580
Polymer				
Minimum carbon black	%	2	2	2
Roll width	m	1.3	1.3	1.3
Roll length	m	60	60	60
Unit weight	kg/m^2	0.45	0.87	0.98
Junction strength	%	95	95	95
Long-term strength at 30°C:				
ULS creep rupture strength, T_{cr}, for 120 yrs	kN/m	27.80	51.03	59.17
ULS creep rupture strength, T_{cr}, for 30 yrs	kN/m	28.84	52.94	61.39

2.7 Design Criteria

The main standard of reference is the Indonesian National Standards for Geotechnical Design Requirements, SNI 8460:2017. According to Tables 44 and 52 of this standard, the minimum factors of safety (FS) that must be met are 1.30 and 1.10 for static and seismic conditions, respectively.

3 RESULTS

Using the TensarSlope software, the global stability can be analyzed while considering the internal stability of every layer of geogrids. Figure 6 presents the analysis for the three-tiered retaining wall under static conditions. The slip surface shown in this figure is the most critical surface, selected from approximately fifty slip surfaces generated during the analysis. The disturbing force was calculated as 15240 kN/m, while the combined resisting force from the soil and facing was 17749 kN/m. An additional 2078 kN/m of resisting force was provided by the geogrids, resulting in a total resisting force of 19827 kN/m. This corresponded to a factor of safety (FS) of 1.301, which is sufficient to meet the required FS of 1.3.

Figure 7 shows the results under seismic conditions The procedure followed the same steps as the static condition. Under seismic conditions, the critical disturbing force increased to 18987 kN/m, approximately 4000 kN/m higher than in static condition. The resisting force from the soil and facing was 20275 kN/m, while the geogrids contributed an additional 1799 kN/m, a total resisting force of 22074 kN/m, which is higher than that in the static case. Therefore, the achieved critical safety factor is 1.163, which is sufficient to meet the required FS of 1.1.

Groundwater and rainwater infiltration effects were not considered in this analysis, as the backfill used is granular fill, which can be considered as free-draining material. In addition, proper installation of surface (top) drainage is also assumed to be adequate.

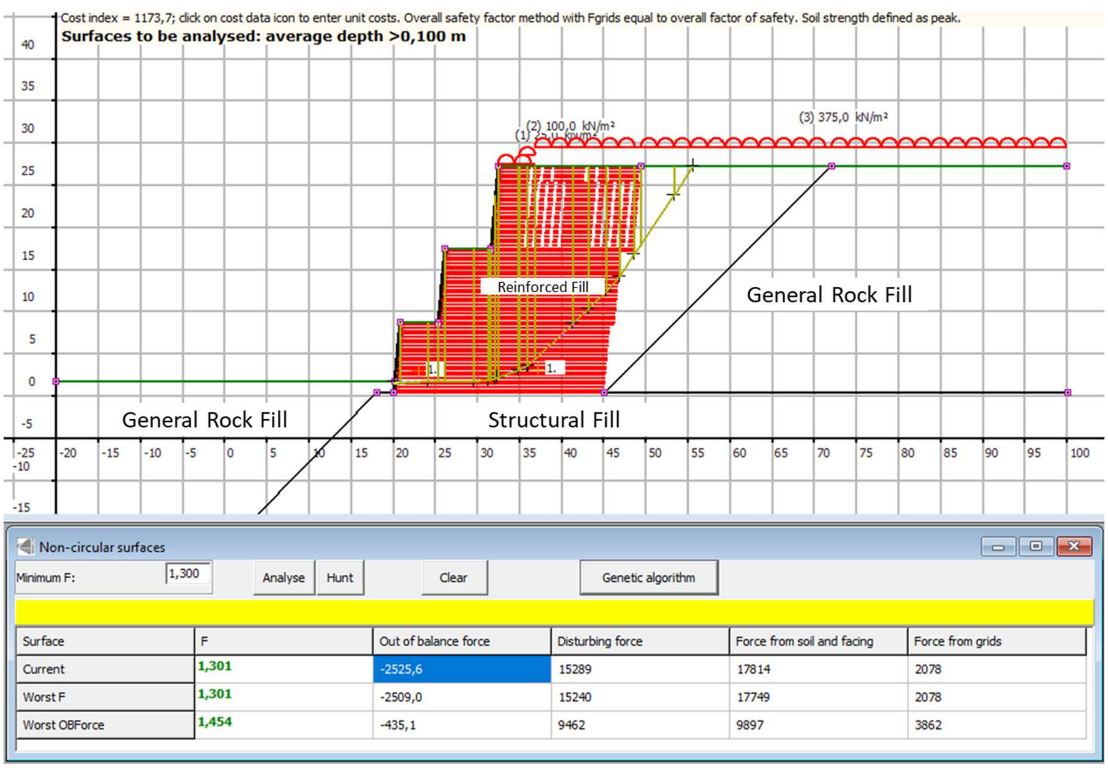

Figure 6. Analysis result under static condition with FS = 1.301

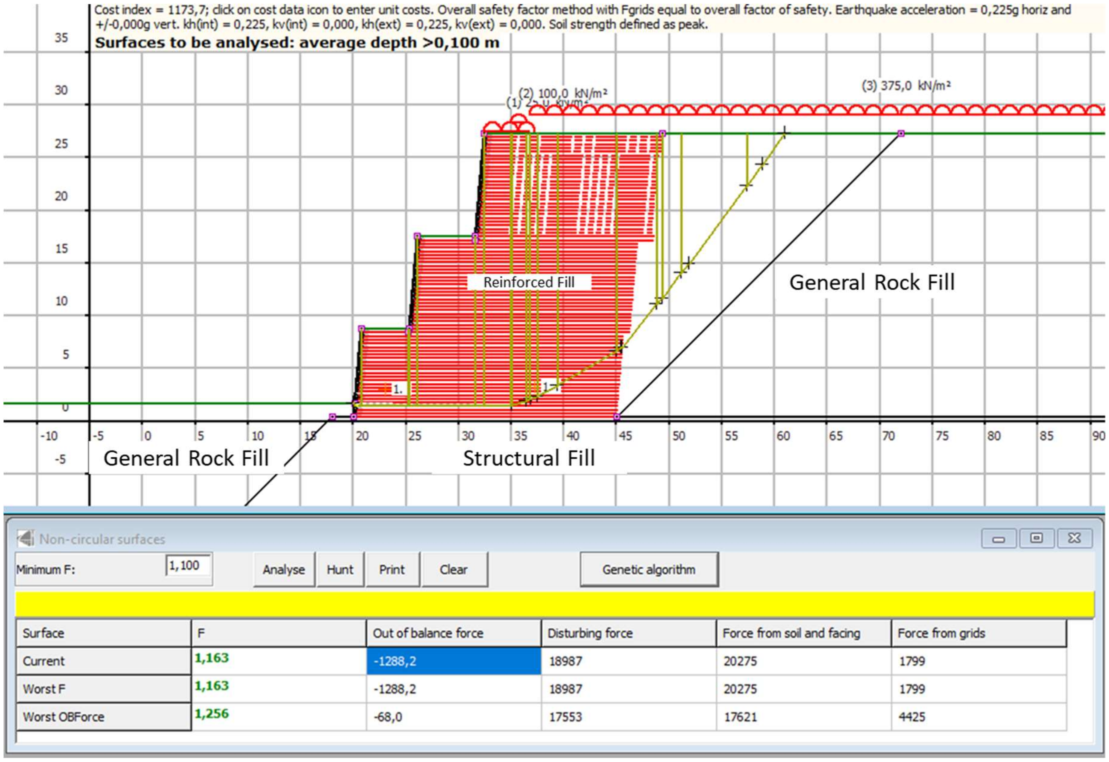

Figure 7. Analysis result under seismic condition with FS = 1.163

4 DISCUSSION AND CLOSING REMARKS

The analysis results indicate that the proposed 26.95 m high three-tiered MSE wall design provides an adequate safety factor, even when subjected to a combination of extremely high static and seismic loads. The FS value under static condition (1.301) and seismic condition (1.163) meets the minimum requirement of 1.30 and 1.10, respectively. The success of the design is attributed to several key factors. First, the use of high-quality granular fill material with an internal friction angle (ϕ') of 40°, providing significant shear resistance to the soil mass. Second, the placement and length of the high-strength uniaxial geogrids in each layer effectively provide tensile resistance and "bind" the soil mass into a coherent and stable block. The reinforcement length, designed up to 25 meters in the lower part of the wall, demonstrates the importance of a massive reinforcement zone to withstand the large lateral earth pressures.

Furthermore, the MSE wall which utilizes welded wire form (WWF) facing system has multiple advantages. This facing not only provides improved erosion control but also allows for steeper wall angles to maximize the space in front of the wall. It is relatively lightweight compared to conventional concrete block facings, facilitating mobilization to remote locations. In addition, the installation process is relatively simple, as it requires only manual labor for lifting and placement without the need for specialized heavy equipment.

This study provides a practical contribution as a design reference for future projects with similar challenges. However, this study has several limitations that should be acknowledged. Groundwater effects and rainwater infiltration were not explicitly considered, as the system was assumed to remain free from the influence of water due to the use of free-draining backfill and surface drainage. Furthermore, deformation and settlement behaviors were not evaluated in this study, even though these factors can be critical in assessing serviceability. Lastly, the analysis relied only on the limit equilibrium method; future investigation using finite element method could offer valuable insights.

DISCLAIMER

The authors declare no conflict of interest.

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