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Evaluation of the bearing capacity characteristics of mattress-reinforced ground focusing on the geotextile's tensile stiffness

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ABSTRACT: Recently, the mattress reinforcement method has become increasingly common, especially in narrow land areas. Despite the establishment of a standard design framework, challenges and limitations regarding the selection of suitable geotextiles and determining the appropriate tensile forces still exist. Therefore, this study investigates the mattress reinforcement performance, focusing on the tensile stiffness of geotextile materials. A series of model tests utilizing aluminum rod laminates and FEM analysis assuming real-scale conditions was carried out to evaluate the effect of geotextile tensile stiffness on the bearing capacity characteristics of the mattress. The model test results revealed that the subgrade reaction was greater during the initial loading stage for the cases utilizing geotextiles with higher tensile stiffness. It is suggested that the increased tensile stiffness of the geotextile enhanced the restraining effect, potentially causing the mattress to behave more rigidly as a foundation. Moreover, for the bearing capacity calculations, the load distribution angle within the mattress was varied to account for the difference in the geotextile stiffness, where the measured and calculated values were compared. In the FEM analysis, a parametric study was conducted by varying the tensile stiffness of the geotextile, the elastic modulus of the soft ground, and the applied load. Based on the analysis, a chart illustrating the relationship between the tensile stiffness of the geotextile and the coefficient of subgrade reaction exerted by the mattress was deduced. The chart confirmed that the larger the tensile stiffness of the geotextile, the larger the coefficient of subgrade reaction, with this effect being more pronounced for smaller rigidity of the soft ground.

KEYWORDS: Mattress, aluminum bar laminate, tensile stiffness of geotextile.

1 INTRODUCTION

In the field of soil reinforcement, the mattress reinforcement method involves placing a geotextile-encased granular material structure (mattress) within the shallow ground. Common granular materials include crushed stone and gravel. This method is commonly used to enhance the bearing capacity and reduce the differential settlement for structures constructed on soft ground (Reinforced Soil Engineering Method Editorial Committee, 1986). The mattress reinforcement technique is widely adopted in Japan due to its effectiveness and relatively simple design procedure. Accordingly, the mattress reinforcement method is deployed for various construction applications, including foundations, retaining walls, box culverts, and embankments.

Recently, the geotextile ground reinforcement method has been further developed and applied, for example, by arranging the reinforcing geotextile elements into three-dimensional grids, known as geocells, which are filled with granular material to increase the stiffness of the ground. These techniques have been utilized in several projects, including road structures (Giroud et al. 2023).

The Japanese mattress reinforcement design method is based on the model shown in Figure 1. The model assumes the equilibrium of forces generated due to the applied load (overburden pressure) and the vertical stress component of the mattress and the supporting soil (Reinforced Soil Engineering Method Editorial Committee, 1986), which can be expressed using Equation (1) and Equation (2) as follows:

$$qB_P = p(B_P + 2H\,tan\;\alpha\,) + M_E \tag{1}$$

$$\begin{aligned} M_E &= S + T \\ &= (\gamma_1\,D_f\,H + \tfrac{1}{3}\,\gamma_2\,H^2)\,K_P\,tan\phi_2 + 2T_D\,sin\theta \end{aligned} \tag{2}$$

Where γ_1 and γ_2 are the unit weight of the subgrade and the mattress filling material, respectively; ϕ_2 is the internal friction angle of the filling material; T_D is the tensile force of the geotextile; and θ is the displacement angle corresponding to the allowable elongation of the geotextile. Moreover, the mattress component M_E in Equation (2) is expressed as the summation of the shear resistance S of the mattress filling material and the uplift resistance, T mobilized by the geotextile at the base of the mattress. Accordingly, M_E functions as the resisting component of the mattress to the applied load, as shown in Equation (1).

Figure 2 illustrates the standard design flow for mattress-reinforced soil (Geogrid Research Committee Specialist Subcommittee, 1990). Generally, the procedure allows for determining the mattress thickness to satisfy the target bearing capacity. However, this design method does not account for the mattress width in relation to the applied loading width (superstructure width), which is believed to be a critical component in estimating the improved ground-bearing capacity in practice. A recent study proposed a simple method for determining the optimal mattress width for a given loading width (Ishikura et al. 2022; Ishikura et al. 2023). The proposed method modifies the conventional evaluation procedure by introducing a new bearing capacity evaluation equation that incorporates a reduction factor to account for the effect of the mattress width.

On the other hand, in the design stage of selecting the reinforcement geotextile material, shown in Figure 2, it is assumed that the tensile strength of the reinforcing geotextile is uniformly distributed without considering the actual tensile force T_D that develops within the reinforcing material itself. Therefore, accounting only for the peak ultimate tensile strength of the geotextile in practice. This assumption might be limited when considering the actual behavior of the mattress under loading. Therefore, this study investigates the role of the tensile stiffness of the geotextile on the reinforced ground bearing capacity, aiming to achieve a more effective design.

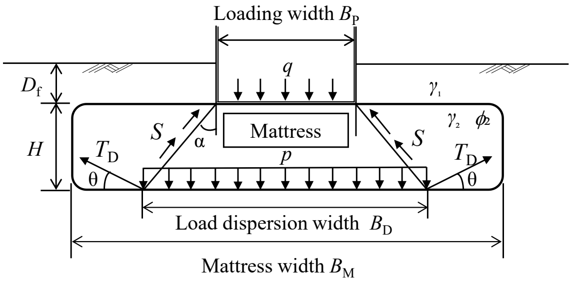


Figure 1. Current mattress design model.

A series of model loading tests using laminated aluminum bars and FEM analysis assuming a full-scale were conducted to evaluate the effect of the geotextile's tensile stiffness influence on the bearing capacity characteristics of the mattress-reinforced ground.

2 MODEL TESTING: EXPERIMENTAL SETUP AND METHODOLOGY

The configuration of the model loading apparatus and the mattress model, constructed by stacking laminated aluminum rods, is illustrated in Figure 3. The used laminated aluminum rods are 5 cm in length. The original ground was constructed by stacking two sizes of aluminum rods with diameters of 1 mm and 1.6 mm, mixed at a weight ratio of 3:2, resulting in a density of 2.13 g/cm^3. Meanwhile, one-sized aluminum rods with a diameter of 2 mm were used as a filling material for the mattress, resulting in a density of 2.22 g/cm^3. The loading was applied vertically through a loading plate with a constant width B_P = 16 cm aligned to the center of the mattress, while the loading speed was set at 0.1 mm/sec.

Maintaining a mattress thickness of H at 2.5 cm, a total of 10 cases were tested while varying the mattress width B_M and the geotextile material. Two types of geotextiles, namely polyester fabric (Material A) and Toraycal Net (Material B), were used to examine the influence of geotextile material stiffness. The tested configurations are summarized in Table 1. The tensile strength for each type of geotextile is depicted in Figure 4.

After setting up the ground model, the loading was applied vertically while measuring the loading force and the vertical displacement until reaching a vertical displacement of 20 mm. Moreover, the tensile forces at the geotextile were measured using strain gauges attached to the bottom side of the mattress at three locations located 6 cm on each side from the center. Meanwhile, a video camera was positioned on the side to capture the deformation of the profile caused by loading. Figure 5 shows a side view of the testing setup for the mattress model in Case 3.

Table 1. Mattress model conditions.

Case	Mattress width B_M(cm)	Material	Tensile stiffness
1	16	A	Small
2	16	B	Large
3	20	A	Small
4	20	B	Large
5	23	A	Small
6	23	B	Large
7	26	A	Small
8	26	B	Large
9	32	A	Small
10	32	B	Large

※Loading width B_p=16 cm: const
Mattress thickness H=2.5 cm: const

3 MODEL TESTING RESULTS AND DISCUSSION

Figure 6 shows the relationship between load intensity q (kN/m^2), tensile force (kN/m) generated in the reinforcement, and vertical displacement S (mm) for Cases 7 and 8 with a mattress width (B_M) of 26 cm. The load intensity, represented by the solid line, is determined by dividing the measured force at the loading plate by the plate area. Meanwhile, the dashed line represents the tensile force corresponding to the average value indirectly determined using the strain gauges installed at the bottom side of the mattress, depicted in Figure 5. Along the load intensity -vertical displacement plane, Case 8, with a larger tensile stiffness geotextile material (Material B), showed a steeper slope at the early loading stages before converging to a constant value. Meanwhile, comparing the development of the

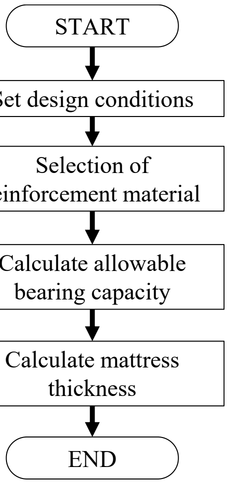


Figure 2. Mattress design flow.

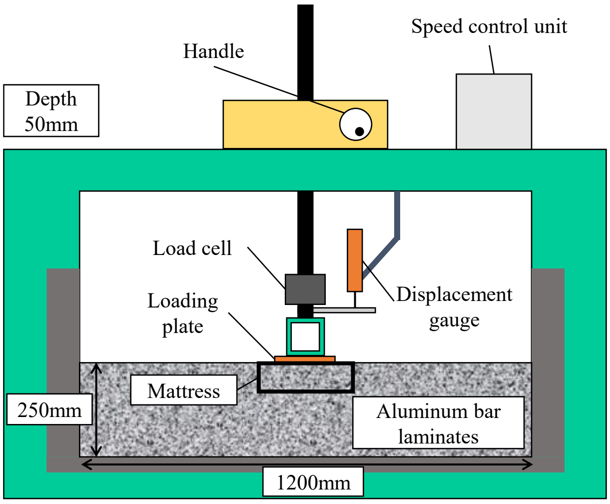


Figure 3. Diagram of the loading test apparatus.

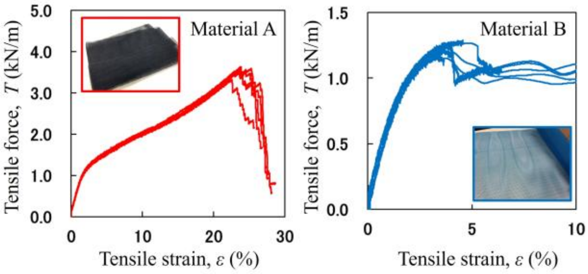


Figure 4. Tensile strength test results for reinforcement.

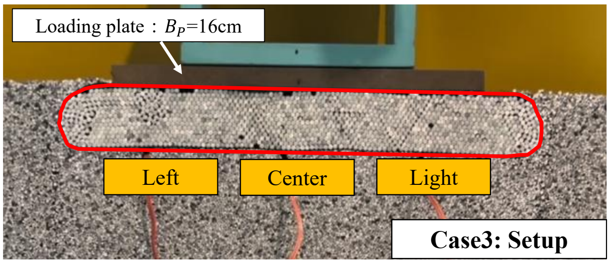


Figure 5. View of the mattress model setup.

tensile force with vertical displacement, the tensile force in Case 7 (Material A) increased at a lower rate compared to Case 8 (Material B), where the tensile force increased rapidly before converging to a constant value after a displacement of approximately 5.0mm.

It can be inferred that using a geotextile with a higher tensile stiffness result in activating the tensile forces component more effectively once the load is applied. Consequently, this induces a higher confinement effect inside the mattress, resulting in an enhanced rigidity of the entire foundation structure (mattress), which facilitates the transfer of the overburden load to the supporting ground.

The vertical strain distribution, corresponding to a vertical displacement of 5 mm, for Cases 7 and 8 are depicted in Figure 7 (a) and Figure 7 (b), respectively. Compared to Case 7 (Material A), Case 8 (Material B) mattresses exhibited a more rigid behavior as a unit, transferring the applied load to the supporting ground more effectively. This behavior subsequently resulted in a wider, wedge-shaped compressive strain profile within the supporting soil, compared to the lower stiffness geotextile, which resulted in a narrower profile below the mattress. The obtained image analysis results also revealed that using a higher stiffness geotextile enhances the rigidity of the entire foundation structure.

Moreover, Figure 8 summarizes the relationship between ultimate bearing capacity versus the mattress width for all the tested cases indicated in Table 1. It must be noted that the ultimate bearing capacity is defined as the maximum loading strength obtained within a vertical displacement in the range of up to 10 mm. The obtained results reveal that:

1. The ultimate bearing capacity of the mattress depends on the mattress width, with a distinct optimum width that maximizes the ultimate bearing capacity.
2. The optimum mattress width that maximizes the ultimate bearing capacity depends on the type of reinforcement material (geotextile tensile stiffness).

Considering a constant mattress thickness H, a method was proposed to determine the optimum mattress width (B_M). It involves introducing a reduction factor (X) to the current design framework, mainly the design criterion expressed in Equation (1) (Ishikura et al. 2023). The proposed method assumes that the optimum width of the mattress's bottom side, affected by the vertical load acting on the mattress's top side, disperses at a specific width, denoted in Figure 1 as B_D. Moreover, the maximum bearing capacity is achieved when the mattress width, B_M, equals the load dispersion width, B_D (Yasufuku et al. 1996; Yasufuku et al. 1998).

The proposed method was tested for the case of using a geotextile with a large tensile stiffness (Material B). A load dispersion angle (α) of 45° is commonly used in practice. However, to account for the higher stiffness of the Material B geotextile, a dispersion angle (α) of 55° is used to compensate for the increase in the total foundation structure (mattress) rigidity, which is a function of the mattress's tensile stiffness. The calculated values using (α) of 55° were compared to the obtained experimental results. The parameters used to calculate the bearing capacity of the tested model experiment are listed in Table 2.

The estimated bearing capacity versus the mattress width using the proposed method is illustrated in Figure 8 and compared to the measured values. Comparing the calculated to the measured bearing capacity, it is suggested that introducing the reduction coefficient X and appropriately setting the load distribution angle α to compensate for the tensile stiffness of the used geotextile might be a simple yet effective method that extends the conventional design framework to determine the optimum mattress width, for a given loading width, while accounting for the geotextile material tensile stiffness.

Table 2. Parameters used to calculate the bearing capacity of the model tests.

Loading width	B_P(cm)	16
Mattress thickness	H(cm)	2.5
Distributed pressure	p(kN/m^2)	12.5
Friction angle of the filling material	ϕ_2(°)	26.7
Unit weight of filling material	γ_2(kN/m^3)	21.8
Load dispersion angle	α(°)	55
Tensile strength (Material B)	T_D(kN/m)	1.25
Deformation angle of the geotextile	θ(°)	20
Reduction factor	X	$1-\left\|1-\frac{B_D}{B_M}\right\|$

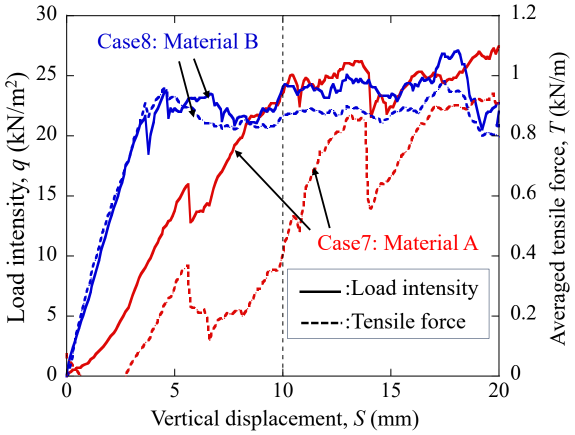
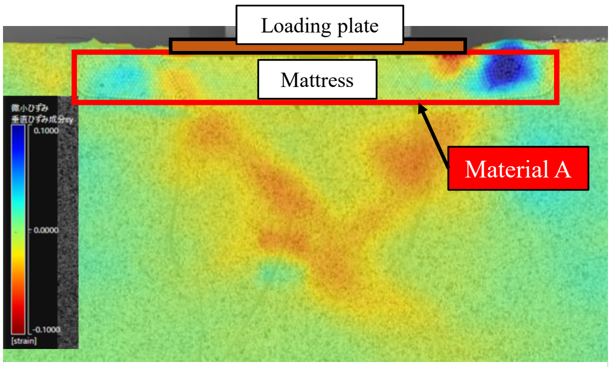
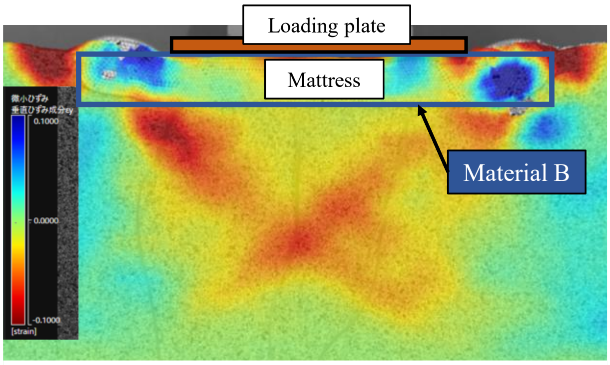


Figure 6. Relationships between load intensity, tensile force and vertical displacement.



(a) Case7 (Material A, B_M= 26 cm, H=2.5 cm)



(b) Case8 (Material B, B_M= 26 cm, H=2.5 cm)

Figure 7. Vertical strain distribution at S= 5.0 mm.

4 FEM ANALYSIS TO ELABORATE ON THE ACTUAL SCALE BEHAVIOR

The obtained experimental results confirmed that the mattress acts as a more rigid structure (foundation) as the tensile stiffness of the geotextile reinforcement increases. In this section, the obtained results regarding the geotextile stiffness were extended, and a bearing capacity FEM numerical analysis of a mattress-reinforced ground, assuming a real-scale model, was conducted to elaborate on the effect of the geotextile's tensile stiffness on the supporting ground performance due to the loading transmitted by the mattress foundation. The ultimate goal is to introduce the reinforcing geotextile stiffness into the bearing capacity design criterion of a mattress-reinforced ground.

A series of simulations using the commercial PLAXIS 2D FEM numerical analysis software was conducted. The simulation model and the used parameters, along with their values, are shown in Figure 9 and Table 3, respectively. Hence, the simulation model cross-section and the parameters used were determined using statistical data from mattress-reinforced ground cases constructed in Japan. The model consists of a mattress with a thickness (H) of 0.4 m and a width (B_M) of 3.0 m, laid on the ground surface. The soil profile has a width of 10.0 m and a depth of 5.0 m, with a load B_p distributed uniformly for 1.8 m at the top of the mattress.

The Mohr-Coulomb (MC) model was used for the supporting (soft) ground, while a geogrid model that considers only the tension resistance was applied for the geotextile reinforcement part. Furthermore, for the mattress filling material, a Hardening Soil (HS) model (PLAXIS, 2019) was used to account for the mattress structure behavior, in which the stiffness inside the mattress increases due to the restraining effect of the geotextile. Generally, the HS model enables accounting for the stress dependency on the deformation coefficient of the ground. Consequently, the deformation coefficient of the filling material was set to increase linearly with the compressive stresses generated inside the mattress, which is associated with the development of tensile forces in the reinforcing material due to the applied loading.

The deformation coefficient for each modeled ground was set based on the reported N values, as shown in Table 3 (JGS, 2004). The simulated cases are summarized in Table 4, where the deformation coefficient of the supporting (soft) ground was divided into four patterns, with the ground N value ranging from 2 to 5. Furthermore, three overburden pressure patterns were used, with q values of 40, 80, and 120 (kN/m²), while the tensile stiffness EA of the reinforcement structure was set to 400, 1000, 10000, and 40000 (kN/m), respectively.

Table 3. Analysis parameters used.

	Soft ground	Filling material	Reinforcement
Constitutive model	Mohr-Coulomb	Hardening Soil	Geogrid
Unit weigh γ (kN/m^3)	14.0	20.0	---
Cohesion c(kN/m^2)	18.0	0	---
Friction angle ϕ (°)	30	40	---
N value	2~5	Around 30	---
Elastic modulus E (kN/m^2)	E = 2800N	E=700N ≒20000	---
Tensile stiffness EA (kN/m)	---	---	*Variable

5 ANALYSIS RESULTS AND DISCUSSION

Figure 10 shows the relationship between the overburden pressure q and the settlement obtained from the conducted analysis for Case 1-1 in Table 4. Compared to the results for the non-reinforced ground, without a mattress represented by the red solid line, it was confirmed that the amount of settlement under the same overburden pressure could be suppressed by installing a mattress reinforcement.

Furthermore, comparing the dashed lines corresponding to mattresses with different tensile stiffnesses, it was observed that the initial subgrade reaction due to the applied overburden pressure increased for mattresses with geotextiles having a higher tensile stiffness. This result is consistent with the tendency observed in model experiments, where increasing the tensile stiffness of the reinforcement (geotextile) results in a stiffer mattress structure (foundation) that induces higher resistance to the applied overburden pressure.

Table 4. Analysis conditions.

Vertical pressure q (kN/m^2)	Elastic modulus of soft ground, E (kN/m^2)			
	5600(N=2)	8400(N=3)	11200(N=4)	14000(N=5)
40	1-1	1-2	1-3	1-4
80	2-1	2-2	2-3	2-4
120	3-1	3-2	3-3	3-4

*Reinforcement Tensile stiffness EA = 400,1000,10000,40000 (kN/m)

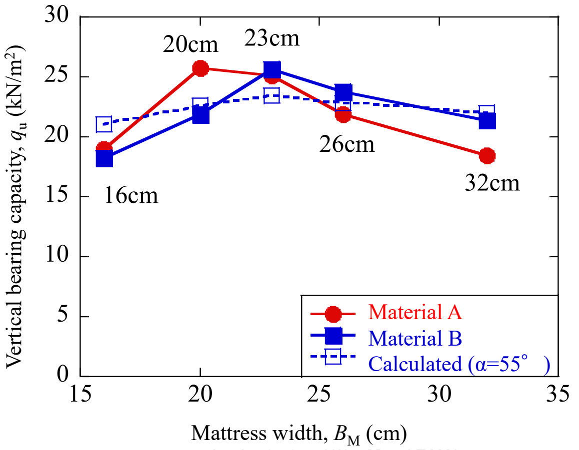


Figure 8. Relationships between vertical bearing capacity and mattress width.

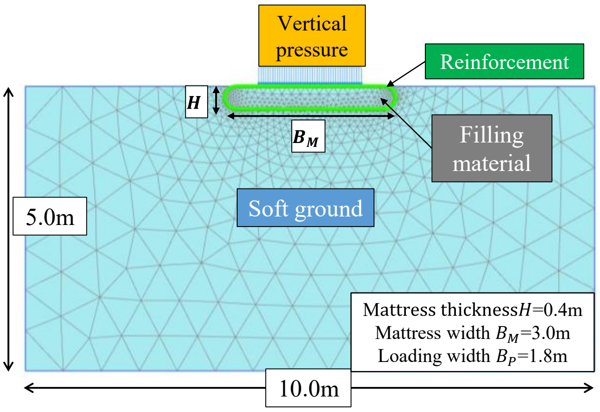


Figure 9. Analytical model of mattress reinforced ground.

Therefore, in future challenges, in order to accurately evaluate the actual behavior of mattress-reinforced ground, it is essential to apply a model that considers increasing the rigidity of the mattress-reinforced ground associated with restraining the volume expansion caused by the dilatancy of the filling material due to the shearing within the reinforcement structure (mattress).

Figure 11 and Figure 12 illustrate examples of the subgrade reaction coefficient ratio (K/K_0) and the tensile stiffness (EA) of the reinforcement (geotextile) relationship obtained from the FEM analysis results for the cases summarized in Table 4. The subgrade reaction coefficient ratio K/K_0 is the ratio of the subgrade reaction coefficient K of the mattress-reinforced ground to the subgrade reaction coefficient K_0 of the non-reinforced ground. The obtained results confirmed that the mattress reinforcement enhanced the ground stiffness by 5-20% in both vertical pressure q = 40 kN/m^2 and 80 kN/m^2. Moreover, the subgrade reaction for mattress-reinforced ground tends to increase as the tensile stiffness of the reinforcement material (geotextile) increases.

Using the ground settlement as an indicator, it was confirmed that the smaller the stiffness (coefficient of deformation) of soft ground, the greater the effect of mattress reinforcement on the ground reaction force, which is directly linked to the settlement behavior. Finally, installing a mattress as a ground reinforcement while selecting the reinforcement material (geotextile) that considers its tensile stiffness affects the immediate settlement (subgrade reaction), regardless of the ground stiffness and vertical applied pressure. Therefore, it is believed that including the reinforcement stiffness as a parameter enhances the effectiveness of the mattress-reinforced ground method for application.

6 CONCLUSIONS

This study investigates the role of the tensile stiffness of the geotextile on the behavior of the mattress-reinforced ground. A series of model loading tests using laminated aluminum bars and FEM analysis assuming a full-scale were conducted to evaluate the effect of the geotextile's tensile stiffness influence on the bearing capacity characteristics of the mattress-reinforced ground. The main findings are delineated as follows:

1. The model test results revealed that the use of a high-tensile-stiffness reinforcement material (geotextile) improves the subgrade reaction force obtained during the early loading stages. It can be inferred that using a higher tensile stiffness material result in activating the tensile forces component more effectively once the load is applied. Consequently, this induces a higher confinement effect inside the mattress, resulting in an enhanced rigidity of the entire foundation structure (mattress).
2. An optimum mattress width, corresponding to the ultimate bearing capacity exists and depends on the type of reinforcement (tensile stiffness). In the bearing capacity calculation method, a new reduction factor X was introduced to the current design Equation (1), where the optimal mattress width can be determined by setting the load dispersion angle α according to the tensile stiffness of the reinforcement, considering the effect of tensile stiffness on the load dispersion angle.
3. A parametric study was conducted using FEM analysis, assuming a full-scale scenario, and a chart was generated to elaborate on the tensile stiffness of the reinforcement (geotextile) in relation to the coefficient of subgrade reaction force exerted by the mattress. It was confirmed that the effectiveness of using mattress reinforcement can be enhanced by selecting a reinforcement (geotextile) with a larger tensile stiffness. It is suggested that introducing a mattress design method that considers the immediate settlement (subgrade reaction) as an indicator requires properly selecting the reinforcement materials (geotextile) by considering the tensile stiffness.

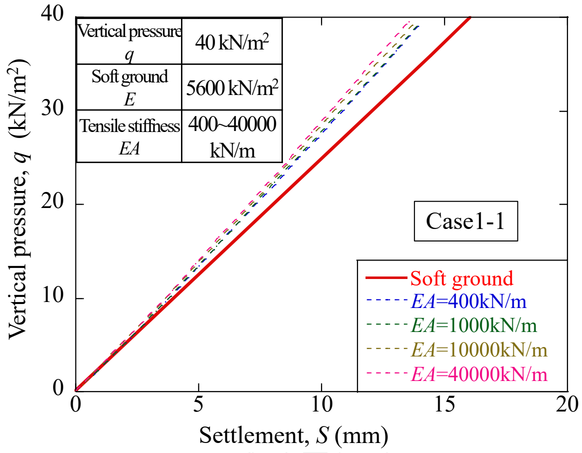


Figure 10. Relationships between vertical pressure and settlement.

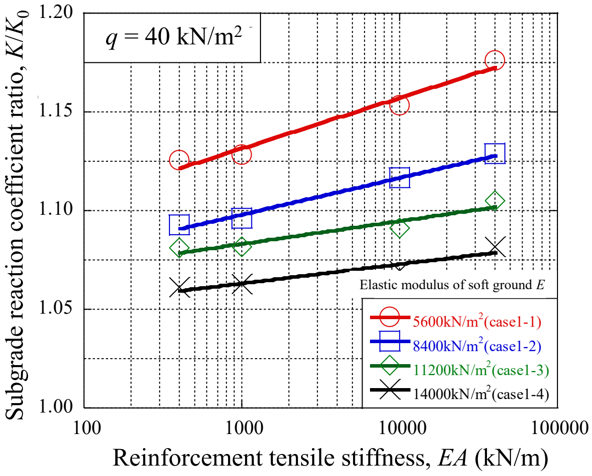


Figure 11. Relationships between the subgrade reaction coefficient ratio and the reinforcement tensile stiffness at vertical applied pressure q = 40 kN/m^2.

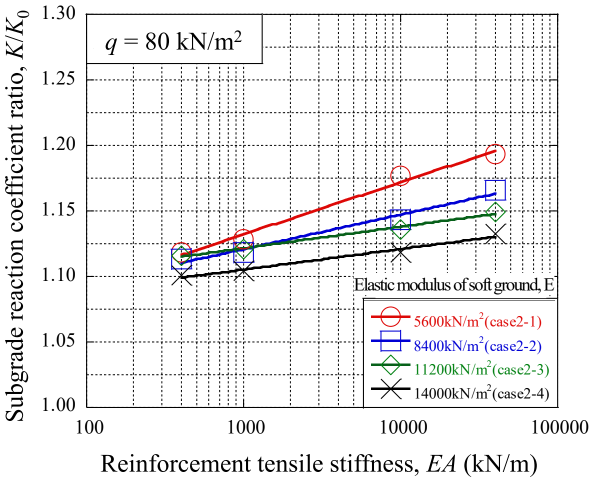


Figure 12. Relationships between the subgrade reaction coefficient ratio and the reinforcement tensile stiffness at vertical applied pressure q = 80 kN/m^2.

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