NEW EARTH REINFORCEMENT METHOD BY SOILBAGS ("DONOW")

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ABSTRACT

This paper presents a new earth reinforcement method by soilbags ("Donow" in Japanese) and its applications to such earth reinforcements as reinforcement for ballast foundations under railway sleeper, reinforcement for soft building foundations and construction of retaining walls. The strength properties of soilbags are studied theoretically and verified through the biaxial compression tests on 2D model soilbags and the unconfined compression tests on real soilbags with various kinds of materials contained. It is found that the high strength of the soilbag is produced due to the tensile force of the bag when the soilbag is subjected to an external force and the bag expands. This reinforcing mechanism contains a "reversal idea" of making use of an external force, which is the "enemy" against the foundation. The earth reinforcement using soilbags has the advantages of improving greatly the bearing capacity for soft ground, resisting flexibly against deformation and being friendly to our environment with less noise during construction and no use of any chemical agents. It also has the effect of reducing traffic- or machine-induced vibration and preventing frost heave.

Key words: bearing capacity, "Donow", frost heave, reinforcement, retaining wall, soft foundation, soilbag, vibration (IGC: K14)

INTRODUCTION

For a long time, people have used soilbags ("Donow" in Japanese) to prevent flow of soils from floodwaters and build temporary structures in case of emergency. However, it seems no applications of soilbags have been used for building a permanent structure. This might be due to a lack of knowledge about the mechanical behaviors of soilbags and the deterioration of soilbags after a long exposure to sunlight, especially the polyethylene-made soilbags which are very sensitive to ultraviolet rays.

As a result of model bearing capacity tests on an assembly of aluminum rods, Matsuoka et al. (1992, 1999) found that the bearing capacity of a foundation can be improved greatly if a part of the foundation is wrapped up with a flexible reinforcer. Inspired by this finding, a new earth reinforcement method by use of soilbags has been developed. In recent years, this new reinforcing method has been successfully applied to such earth reinforcements as the reinforcement for a ballast foundation under railway sleepers, the reinforcement for soft building foundations and the construction of retaining walls. In these applications, attention was paid to protect soilbags from sunlight by either embedding them in the ground or using thin facing concretes. Chemical experiments show that the polyethylene-made bags can be sustained for a long time (about 50-60 years) if they are

protected from sunlight. During the experimental studies and application practices, many advantages and unexpected effects of the reinforcing method by soilbags have been found, which are summarized as follows:

- It is reasonable to wrap up distinct soil with a bag. The soilbag takes effect by making use of external forces, which are the "enemies" to a foundation.
- It is possible to increase the bearing capacity (load) of a soft building foundation by 5 ~ 10 times.
- It is environment-friendly due to no use of any cement or chemical agents.
- It is silent during construction.
- No special construction equipment is needed. It is even possible to construct merely by manpower.
- Soilbags are light. Their weights are similar to the weight of soil.
- The materials inside soilbags may be any construction wastes such as concrete, asphalt, tire and tile wastes as well as the granular remains after garbage treatment. Thus, soilbags can also contribute to the recycle of waste materials.
- The soilbag itself has an unbelievably high compressive strength.
- It has an effect of reducing traffic- or machine-induced vibration. It may also be possible to reduce earthquake vibration.
- It has an effect of preventing frost heave if coarse

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Fig. 1. Schematic view of model bearing capacity test device

granular materials are put into the bags.

- Waterlogged soft ground may also be reinforced by soilbags.

In this paper, we first introduce the conception of the earth reinforcement method by soilbags in detail and present the strength properties of soilbags subjected to external forces from different directions. Then, we report several application cases in earth reinforcement and measurement of traffic-induced vibration in a field where the soft foundations have been reinforced by soilbags.

CONCEPTION OF EARTH REINFORCEMENT METHOD BY SOILBAGS

The study started with model bearing capacity tests on an assembly of 50 mm long aluminum rods with diameters of 1.6 mm and 3 mm and a ratio of 3:2 by weight. Figure 1 shows the schematic view of the test apparatus. The assembly of the aluminum rods had a void ratio of about 0.23 and a dry density of 21.6 kN/m^3 . The advantages of modeling ground by aluminum rod mass are known as follows:

- The specific gravity G_s of aluminum rods (2.69) is near to that of soil particles (about 2.65).
- It is unnecessary to support the front and back faces of the aluminum rod mass.
- It is easy to draw mark lines on the front face of the aluminum rod mass using a felt-tip pen to observe the particle movements.

A series of bearing capacity tests were carried out on this aluminum rod mass with different reinforcement ways by pieces of paper (a model of flexible reinforcer) with a tensile strength of $33 \text{ N/cm} \sim 41 \text{ N/cm}$ and a weight of 64 g/m^2 . The target for the tests was to improve the bearing capacity (load) by 10 times (Matsuoka et al., 1992), which implied the need of developing a new reinforcement method different from the conventional ones such as placing reinforcers (geotextiles, nets, mattresses, strips, etc.) horizontally into grounds (e.g. Binqest and Lee, 1975a, 1975b; Hirao et al., 1997; Huang and

Fig. 2. Reinforcement with a piece of horizontal paper (30 cm long and 3 cm deep)

Fig. 3. Measured load Q against settlement S of the footing

Tatsuoka, 1990). Nevertheless, we started our tests in a conventional reinforcing way, i.e. placing a piece of 30 cm long traditional Japanese paper, a kind of model flexible reinforcer, horizontally into the aluminum rod mass 3 cm deep beneath the footing (Fig. 2). The test result is shown in Fig. 3 in plots $\blacktriangle$. It is seen that the increase in the bearing capacity is very little. This is because the aluminum rods slip above the horizontal paper, as shown in Fig. 2, and the horizontal paper deforms following the model ground. Then, we considered the elastically calculated orientations of the principal stresses beneath a footing, as shown in Fig. 4. It is understood from Fig. 4 that the minor principal stress, σ_3 , or the minor principal strain, ϵ_3 , (the tensile principal strain) takes a half-circular shape. Since the flexible model reinforcer of Japanese paper cannot resist against bending, it is a tensile reinforcer. Thus, it is expected to be most effective in reinforcing the foundation by placing the tensile reinforcer in a half-circular shape in the tensile principal strain direction. The tests were thereby carried out in such a way, but the increase in the bearing capacity remains slight (plots $\square$ in Fig. 3) due to the escape of the

Fig. 4. Elastically calculated orientations of principal stresses under a footing

Fig. 5. Reinforcement with a half-circular paper but open in two sides of the footing

Fig. 6. Big slip lines after wrapping up a part of aluminum rods

aluminum rods from the two lateral sides of the footing (see Fig. 5). To overcome this problem, both the two sides of the paper were extended to the bottom of the footing, i.e. a part of the aluminum rods was completely wrapped up, as shown in Fig. 6. Consequently, the slip lines became deeper and wider (Fig. 6) and the bearing capacity (load) of the model ground increased by 2~3 times (plots ○ in Fig. 3). Figures 7 and 8 show the enlarged picture of the wrapped part and the numerically simulated results by distinct element method (Yamamoto et al., 1995), respectively. It is observed that the wrapped part is very solid and deforms following the footing, behaving as if it were a part of the footing. The interparti-

Fig. 7. Enlarged picture of the half-circular wrapped part subjected to an external force

(a) Displacement vectors relative to the footing

(b) Interparticle forces

Fig. 8. Numerically simulated results by DEM (Yamamoto et al., 1995)

cle forces inside the wrapped part are considerably larger than those outside it. This is because the external force acting on the footing induces a tensile force in the wrapping reinforcer and the tensile force thereafter acts on the aluminum rods inside the wrapped part. This argument will be formularized in the latter part of this paper. As the external force is usually an “enemy” against the foundation, the argument contains a “reversal idea” of making use of the foundation’s “enemy” to reinforce the foundation.

As the wrapped part behaves as if it were a part of the footing, it is expected to increase the bearing capacity by enlarging the width B' of the half-circularly wrapped part. The tests were thereby carried out by enlarging the width B' of the half-circularly wrapped part to 1.5, 2 and 3 times the width B ($= 10$ cm) of the footing. Figure 9 shows their results with respect to the load Q vs. settlement S relationship. As predicted theoretically, the ultimate bearing capacities increase by $(B'/B)^2$ times the

Fig. 9. Increase of the bearing capacity with an increase in the width B' of the wrapped part (footing width $B=10\text{ cm}$, $B'=1.5B$, $2B$, $3B$)

Fig. 10. Double slip lines in the model ground with 15 cm square area wrapped up

value in the case of no reinforcement. But, it is found that the settlement S before the ultimate bearing capacity, which is usually undesirable in earth reinforcement, increases accompanying enlargement in the width of the wrapped part.

To reduce this harmful settlement, a way of dividing a big wrapped part into several small ones were considered, for example, a square paper-wrapped part with an area of 15 cm by 15 cm ($=225\text{ cm}^2$) was divided into 6 small ones of 15 cm by 2.5 cm with the same total area. The measured loads Q of the footing before and after dividing the big square wrapped area into 6 small ones are plotted against the settlement S of the footing in Fig. 12. Figures 10 and 11 show the slip lines occurring in these two cases, respectively. It is seen from Fig. 10 that slip lines first take place inside the big square wrapped part, and subsequently other big slip lines take place beneath the entire big wrapped part when the big wrapped part becomes solid and functions as a part of the footing. This is the reason for the two stages in the $Q \sim S$ curve and the large settlement S at the ultimate bearing capacity in the

Fig. 11. Big slip lines in the model ground by dividing 15 cm square area into 6 layers

Fig. 12. Differences of the load-settlement curves before and after dividing a big wrapped area of $15\text{ cm} \times 15\text{ cm}$ into 6 small ones

big wrapped case, as illustrated in Fig. 12. However, after dividing this big wrapped area into 6 small ones, big slip lines occur only beneath the lowest wrapped layer (see Fig. 11). Correspondingly, the initial gradient of the $Q \sim S$ curve is steep and the settlement S at the ultimate bearing capacity is small, too. This suggests that the increase in ultimate bearing capacity within a small settlement can be achieved by dividing a big wrapped area into several small ones. This leads to consideration on the well-known soilbags. Then, the tests were carried out with several 2D model soilbags of 4 cm by 1.5 cm arranged in different ways as shown in Fig. 13. The model soilbag was made by wrapping up small amounts of the aluminum rods with Japanese paper. Figure 14 gives the test results corresponding to Fig. 13, illustrating that the ultimate bearing capacity increases with increasing numbers of the model soilbags and its value is at least twice larger than that in the case of no reinforcement, irrespective of their arrangements. Thus, it may be an effective reinforcement method to arrange several soilbags under a foundation. If the soilbags are connected, the reinforcing effect is more effective. Figure 15 shows a test with soilbags arranged triangularly and connected horizontally, and the result is shown in Fig. 16. It is seen that the

Fig. 13. Arrangement of 2D model soilbags

Fig. 14. Increase of the bearing capacity with the increasing numbers of the model soilbags corresponding to Fig. 13

Fig. 15. Flexible deformations of the horizontally connected soilbags under extremely large settlement of the footing

Fig. 16. Results of the tests shown in Photo. 6: The target of increasing the bearing capacity by 10 times is achieved

Fig. 17. Stresses acting on 2D model soilbag and on particles inside the soilbag

ultimate bearing load Q by this reinforcement is nearly 10 times that in the case of no reinforcement, achieving our initially set target. From Fig. 15, one can also see that the soilbags deform flexibly with the movement of the reinforced ground.

STRENGTH PROPERTIES OF SOILBAGS

Apparent Cohesion due to the Bag's Tension

Soilbags take effect when they are subjected to external forces. The reason can be illustrated by considering the strength of a 2D model soilbag. Figure 17(a) shows a 2D soilbag subjected to external principal stresses, σ_{1f} and σ_{3f} . Under the application of σ_{1f} and σ_{3f} ($\sigma_{1f} > \sigma_{3f}$), the soilbag usually tends to be flat with an extension of the total

perimeter of the bag. As a result, a tension T is induced in the bag. In a real soilbag, the induced tension T may be not uniform in the bag. But here, it is assumed to be constant throughout the bag. This tension produces an additional stress that acts on the soil particles inside the soilbag, whose components are expressed as:

$$\left. \begin{aligned} \sigma_{01} &= 2T/(B \times 1) \\ \sigma_{03} &= 2T/(H \times 1) \end{aligned} \right\} \quad (1)$$

where B and H are the width and height of the soilbag, respectively. Thus, the stresses acting on the soil particles inside the soilbag are the combined result of the externally applied stresses and the additionally produced stresses by T , as shown in Fig. 17(b). At failure, the following equation holds (Chen, 1999; Matsuoka et al., 2000a):

$$\sigma_{1f} + \frac{2T}{B} = K_p \left(\sigma_{3f} + \frac{2T}{H} \right), \quad \text{where } K_p = \frac{1 + \sin \phi}{1 - \sin \phi} \quad (2)$$

Obviously, Eq. (2) holds in two-dimensional stress state, and the three-dimensional confining effect is not taken into account. It is seen from Eq. (2) that the confining effect induced by the tension T is stronger in σ_3 direction than in σ_1 direction, so the large ratio of B/H of the soilbag benefits the reinforcement.

By comparing Eq. (2) with the strength expression of $\sigma_{1f} = \sigma_{3f} K_p + 2c\sqrt{K_p}$ for a cohesive-frictional material, we can obtain the expression of the apparent cohesion c of the soilbag due to its tension T .

$$c = \frac{T}{B\sqrt{K_p}} \left(\frac{B}{H} K_p - 1 \right) \quad (3)$$

This is to say, a frictional material is turned into a cohesive-frictional material merely by wrapping it up with a bag.

Verification of the Apparent Cohesion by Biaxial Compression Tests on Model Soilbags

In order to verify the Eqs. (2) and (3), a number of biaxial compression tests were performed on 2D paper-wrapped model soilbags (Fig. 18). The 2D model soilbag is made by wrapping up the same aluminum rods as used

in the footing bearing capacity test with a piece of very weak paper. The use of the very weak paper (a tensile strength $T = 0.36 \text{ kgf/cm} = 3.53 \text{ N/cm}$) is due to the limitation of the loading capacity in our biaxial compression test apparatus. The angle of internal friction, ϕ , of the aluminum rod mass is equal to 25° . The 2D model soilbag has dimensions of 15 cm wide by 3.75 cm high. The biaxial compression test apparatus allows the vertical and lateral loads to be applied separately. To minimize the boundary influence of the apparatus, three model soilbags are piled up to construct a specimen. The measured stresses acting on the model soilbags at failure are expressed with the solid Mohr's stress circles in Fig. 19(a). In the tests, the failure of the model soilbags takes place when the bags (paper in 2D model soilbags) break down, accompanying a rapid decrease in the stress ratio as shown in Fig. 19(b). It is seen from Fig. 19(a) that the soilbag has a strength characteristic like a cohesive-frictional material (c - ϕ material). By using the frictional angle $\phi = 25^\circ$ of the aluminum rods and the apparent cohesion $c = 14 \text{ kPa}$ calculated from Eq. (3), the failure

Fig. 18. Schematic view of biaxial compression test on 2D model soilbags

Fig. 19. Results of biaxial compression test on 2D model soilbags: (a) Mohr's stress diagrams and failure lines and (b) Typical stress-strain relationship

line (solid straight line) of the model soilbags is drawn in Fig. 19. It is seen that the predicted failure line is nearly tangent to the measured Mohr's stress circles at failure, indicating the reasonability of Eqs. (2) and (3). The broken Mohr's stress diagrams in Fig. 19 represent the stresses acting on the inside materials at failure obtained by combining the externally applied stresses with the additionally produced stresses due to tension at failure, $T=3.53$ N/cm, of the paper-made bag. The envelop of these broken Mohr's stress circles is a straight line passing through the origin with an inclined angle of 25° , which is equal to the internal friction angle of the aluminum rod mass inside the model soilbag. That is to say, the material inside the soilbag is maintained as a frictional material when it is wrapped up with a bag. This fact also supports the assumption that the material inside the soilbag reaches a critical equilibrium simultaneously with the soilbag during the derivation of Eq. (2).

Unconfined Compression Tests on Real Soilbags with Various Kinds of Materials Contained

A series of unconfined compression tests (see Fig. 20) have been carried out on several kinds of real soilbags. In each test, three soilbags are used to minimize the effect of the friction on the upper and lower ends of the loading unit. The materials inside the soilbags cover artificially crushed stones, Shirasu, coal ashes, volcanic ashes and dewatered muddy silt. Three kinds of bags, PE-bag

Fig. 20. Unconfined compression test on real soilbags

(made of polyethylene), PP-bag (made of polypropylene) and PE (UVR)-bag (made of polyethylene with a property of resisting ultraviolet ray), are used. One soilbag has an initial size of about $40\text{ cm} \times 40\text{ cm} \times 10\text{ cm}$. Table 1 summarizes the measured loads at failure and the corresponding compressive strengths. The load at failure can be predicted from Eq. (2) by taking into consideration $\sigma_3 = 0$ at the unconfined compression test. For example, in the case where the bag is made of PE and the material inside the bag is crushed stones, the load F of the soilbag at failure is predicted as follows:

$$\begin{aligned} F &= \sigma_{1f} \times B \times L = (2T/B) \{ (B/H)K_p - 1 \} \times B \times L \\ &= 2T \{ (B/H)K_p - 1 \} \times L \\ &= 2 \times \{ (0.4/0.1) \times 5.55 - 1 \} \times (T \times L) \\ &= 42.4 \times (T \times L) = 42.4(1.2 \times 0.4) \\ &= 20.4tf = 200\text{ kN} \end{aligned} \quad (4)$$

where L is the length of the soilbag. The calculated value of 200 kN is smaller than the measured values of 230 ~ 290 kN. The reason for this is as follows: a) the three dimensional confining effect is not accounted for in Eq. (2); b) the initial dimensions of the soilbags are used in the prediction of Eq. (4) because of no record of the dimensions of the soilbags at failure. It is found from the prediction of Eq. (4) that the load at failure F for the tested soilbag, 200 kN, is more than 40 times the tensile strength of the bag of $1.2tf/m \times 0.4\text{ m} = 0.48tf = 4.7\text{ kN}$. This extremely high bearing load of soilbag results from the apparent cohesion c due to the tension T of the bag. Whereas, the strength of usual concrete is known to be about 20 MPa, it can be seen from Table 1 that the soilbag has a compressive strength as high as about 1/10 times that of usual concrete. Such high strength is enough for earth reinforcement. Moreover, it is seen from Table 1 that the soilbags made of Shirasu, coal ash, volcanic ash and dewatered muddy silt have compressive strengths as high as the soilbags made of good materials of crushed stones. This suggests that soilbags may provide us an effective way of recycling construction wastes or naturally produced wastes. Here, it is pointed out that the soilbags were compacted with a plate vibrator to reduce the deformation before the bag tension takes place. As the angles of internal friction of Shirasu, coal

Table 1. Summary of the results of unconfined compression tests on various soilbags

Bag material	PE	PS	PE	PE	PE	PS (UVR)	PS (UVR)
Materials inside soilbag	Crushed stones	Crushed stones	Shirasu	Dry coal ash	Wet coal ash	Volcanic ash	Dewatered muddy silt
Load at failure (kN)	230 ~ 290	550 ~ 650	680	266	510	584	240
Compressive strength (MPa)	1.4 ~ 1.8	3.4 ~ 4.1	4.3	1.7	3.2	3.7	1.5

Note: PE-Bag made of polyethylene with tension strength of about 12 kN/m; PS-Bag made of polyester with tension strength of about 20 kN/m; PS(UVR)-Bag made of polyester having a property of resisting against ultraviolet rays. Shirasu is volcanic sand widely spread in Kyushu region of Japan. Coal ash is a by-product from thermal electric power plants. Volcanic ash is taken from Miyake Island, where a large volcano erupted in 2000. Dewatered muddy silt is the by-product during cleaning treatment of drinking water. One soilbag has an initial size of $40\text{ cm} \times 40\text{ cm} \times 10\text{ cm}$.

Fig. 21. Biaxial compression tests on 2D model soilbags with $\delta = 15^\circ$: Tests are also performed on the inclined soilbags with $\delta = 0^\circ, 30^\circ, 45^\circ, 60^\circ$ and 90°

ash, volcanic ash and dewatered muddy silt were not investigated, the failure loads of the soilbags with these materials inside the bags were not predicted.

Compressive Strengths of Soilbags Subjected to Inclined External Forces

As seen in Fig. 17, Eqs. (2) and (3) are derived on the condition that the direction of the externally applied principal stress σ_{1f} is identical with the short axis of soilbags. However, in practice, soilbags may undertake external forces from any direction. Here, we define δ as the angle between the external principal stress σ_1 and the short axis of soilbags. It is considered that the apparent cohesion c defined by Eq. (3) varies with the angle δ . This is investigated through a series of biaxial compression tests on 2D model soilbags (Matsuoka et al., 2002). One 2D model soilbag is 5 cm wide by 1 cm high and is made by wrapping up aluminum rods (1.6 mm and 3 mm in diameters, 50 mm long and mixed with a ratio of 3:2 by weight) with a piece of weak paper having a tensile strength T of about 8.24 N/cm. Since the biaxial compression test apparatus allows external forces to be applied on the specimen (30 cm by 30 cm) only in the vertical and horizontal directions, the model soilbags are piled up with different inclination angles of δ ($=0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ$ and 90°) to the horizontal direction, as shown in Fig. 21. Figure 22 shows the measured Mohr's stress diagrams at failure for $\delta = 0^\circ, 15^\circ, 30^\circ$ and 45° . From the tangent lines of these Mohr's stress diagrams (not shown in Fig. 22), the apparent cohesions corresponding to different inclination angles δ of the model soilbags, representing as $c(\delta)$, are obtained, which are then normalized by the apparent cohesion $c(\delta = 0^\circ)$ in the case of $\delta = 0^\circ$ and plotted against δ in Fig. 23. The dotted lines in Fig. 23 are drawn with a theoretical prediction (Chen, 1999), which illustrate the increase of $c(\delta)$ with an increasing internal friction angle ϕ of the materials inside soilbags. For the sake of safety, the variation of $c(\delta)$

Fig. 22. Mohr's stress diagrams measured from the biaxial compression tests and failure lines predicted with $\phi = 25^\circ$ and apparent cohesions c from Eq. (5) under different inclination angles δ of the model soilbags

Fig. 23. Variations of the apparent cohesions of the inclined soilbags $c(\delta)$

measured from the tests (plots $\bullet$) is fitted as the solid line in Fig. 23 and expressed as follows:

$$c(\delta) = \begin{cases} c(\delta = 0^\circ) \cdot \cos 2\delta & (0^\circ \leq \delta \leq 45^\circ) \\ 0 & (45^\circ \leq \delta \leq 90^\circ) \end{cases} \quad (5)$$

where $c(\delta = 0^\circ)$ is calculated from Eq. (3). By using the cohesions $c(\delta)$ calculated from Eq. (5) and the internal friction angle $\phi = 25^\circ$ of the aluminum rod mass, the failure lines for $\delta = 0^\circ, 15^\circ, 30^\circ$ and 45° are presented in Figs. 22 (a)–(d), respectively. It is known from Eq. (5) and Fig. 22 that the apparent cohesion $c(\delta)$ decreases with increasing inclination of angle δ and it becomes zero when $\delta \geq 45^\circ$.

Tensile Strengths of Soilbags

Commonly, there is no tensile strength for a frictional material. But if a frictional material is put into a bag to construct a soilbag, the soilbag can stand a tensile force; that is to say, the soilbag has a tensile strength. This is verified through a series of pulling tests on a 2D model soilbag as shown in Fig. 24 (Matsuoka et al., 2002). The 2D model soilbag is the same as used in the biaxial compression tests (see Fig. 21) except the difference in its

Fig. 24. Pulling 2D model soilbag horizontally with no vertical load acted on it

Fig. 25. Mohr's stress diagrams measured from the pulling tests and the theoretical failure lines

size. Figure 25 shows the Mohr's stress diagrams at failure (breakdown of the wrapping paper) obtained from the pulling tests and the failure lines predicted by Eq. (3). It is seen that the Mohr's stress diagrams vary with the sizes of the soilbags as well as the tensile strengths of the bags, and the failure lines predicted by Eq. (3) are tangent to the Mohr's stress diagrams. This suggests that the tensile strengths of soilbags can be predicted theoretically in the same way as compressive strengths. In practice, the tensile strengths of soilbags are usually ignored for the sake of safety although they may actually exist in such cases where the soilbags are connected as used in constructing retaining walls.

Failure Criterion of Soilbags

It is known that soilbags have both compressive strengths and tensile strengths, and the compressive strengths decrease accompanying with a decrease in the apparent cohesion $c(\delta)$ when they are subjected to an inclined external force ($\delta > 0$). Figure 26 shows consideration of the failure criterion of soilbags in a real design. The Mohr's stress diagram in Fig. 26 represents the stress states of soilbags at failure in the case of $\sigma_3 = 0$, where

Fig. 26. Failure criterion of soilbags

$c(\delta)$ is calculated by using Eqs. (3) and (5). As stated before, soilbags have tensile strengths when they are connected. So, for the connected soilbags, the failure criterion may be taken as $\tau_f = c(\delta) + \sigma \cdot \tan \phi$, as shown in the bold dotted straight line in Fig. 26. Usually, only the compressive strength in the range of $\sigma \geq 0$ is considered for the sake of safety. Since one cannot apply externally any tensile forces on the unconnected soilbags, the strengths of the unconnected soilbags are equal to zero in the range of $\sigma_3 < 0$. When $\sigma_1 = \sigma_3 = 0$ ($\sigma = 0$), no tensile force T takes place in the bag, resulting in $\tau_f = c = 0$. Thus, for the unconnected soilbags, the strength line must pass the origin. When $\sigma_3 \geq 0$ (the normal stress on the failure plane $\sigma \geq \sigma_F$, where σ_F is the normal stress on the failure plane in accordance with $\sigma_3 = 0$), the strength of the unconnected soilbags is characterized by the straight line FF' in an expression of $\tau_f = c(\delta) + \sigma \cdot \tan \phi$. In the range of $0 < \sigma \leq \sigma_F$, the strength of the unconnected soilbags increases along the arc OF in Fig. 26 until the bag reaches its tensile strength. Therefore, in a real design, the failure criterion of the unconnected soilbags may be characterized with such a curve OFF' that consists of the arc OF and the straight line FF' , as illustrated in the bold line in Fig. 26.

APPLICATIONS OF SOILBAGS IN EARTH REINFORCEMENTS

Reinforcement for a Railway's Ballast Foundation

Since the ballast is placed near the surface of the railway ground, the confining stress σ' of the ballast due to its gravity is very small, and so is its shear strength τ_f ($\tau_f = \sigma' \cdot \tan \phi$). This is the reason for the large lateral movement of the ballast and the harmful settlement of the railway sleeper. But, if the ballast is wrapped up with a reinforcer like a soilbag, the shear strength of the ballast foundation increases due to the tension of the bag (reinforcer) that is produced when the wrapped ballast dilates and the bag is extended under the train loading. This will lead to an increase in the bearing capacity of the ballast foundation and the reduction in the settlement of the sleeper. The effectiveness of this reinforcing method has been verified through a series of model and prototype tests on the assemblies of aluminum rods, crushed stones and real ballast foundation (Matsuoka and Liu, 1999; Kachi et al., 1997; Matsuoka et al., 1998). Here, we report an application case of such a reinforcing method in

Fig. 27. Reinforcement of a ballast foundation under railway sleeper

Fig. 28. Schematic view of using soilbags to reinforce a ballast foundation in a local Japan railway line

a local Japan railway line with a reinforced length of about 13 m (Matsuoka et al., 2000d).

Figure 27(a) shows the site where the reinforcement by soilbags was implemented. It is located at the slope of a hill where water and soils from the hill can overflow the railways in rainy seasons and a serious mud pumping once took place in the roadbed. Before the reinforcement by soilbags, the settlement of the sleeper was larger than 20 mm so that usual maintenance by inserting a new ballast into the foundation with dynamic tamper had to be performed frequently. Figure 28 shows the schematic view of reinforcing this weak railway foundation with soilbags.

The construction procedures are as follows: 1) Remove the sleepers from the rails and excavate all the ballast foundation (about 42 cm) and 10 cm roadbed founda-

tion; 2) Compact the excavated foundation with vibrators and then place a layer of usual soilbags. The usual soilbags, having sizes of about 40 cm long by 40 cm wide by 10 cm high, are made of No. 5 crushed stones and polyethylene bags. They were connected mutually using high strength ropes and compacted thoroughly with vibrators. Figure 27(b) shows the completion of compacting these connected soilbags. 3) Place a layer of special soilbags on the connected soilbags in the parts beneath the sleepers and compact these special soilbags with vibrators, as shown in Fig. 27(c). The special soilbags, having sizes of about 35 cm by 60 cm by 15 cm, are made of fresh ballasts and high strength Vectron bags. 4) Reset the sleepers and insert fresh ballasts into the intervals between the sleepers and the soilbags. Finally, the ballasts are compacted with dynamic tampers. It took two nights

Fig. 29. Measured settlements of the sleeper before and after the reinforcement by soilbags

to complete the reinforcing work of this 13 m long railway foundation, because this work can only be done after the pass of the final train and prior to the start of the first train next day. Figure 27(d) shows half completion of the reinforcement. In addition, to prevent the entrance of the hill soils into the railway, a small retaining wall was built with soilbags and waterproof sheets. A drain trench was also built with the special soilbags between the small retaining wall and the hill to divert the hill water.

The settlements of the railway sleepers measured at the rail joint where the foundation was reinforced with soilbags are plotted against the elapsed time for more than three years in Fig. 29. It can be seen that the settlements reached more than 20 mm before the reinforcement by soilbags, although maintenance with dynamic tamper was frequently implemented, but they were reduced to less than 10 mm after reinforcement by soilbags during more than three years. Moreover, the average oscillation acceleration of the trains was reduced from 0.12 g (g: gravity acceleration) to 0.04 g after reinforcement by soilbags, accompanying the reduction of the settlements of the railway sleepers. This may be contributed to the improvement of the weak ballast foundation and the absorption of the train vibration energy due to the small deformation of the soilbags.

Due to various influences during construction, the sleepers have an instant settlement of about 14 mm after setting up soilbags that is considered to be unavoidable and can be recovered by dynamic tampers in only one time.

Reinforcement for Soft Building Foundations

So far, soilbags have been used to reinforce several hundreds of soft building foundations in Japan. Figure 30 shows a typical arrangement of soilbags used to reinforce the building foundation with N -values as low as 1~2 and Fig. 31 shows such a typical construction field (Matsuoka et al., 2000b). Four layers of soilbags are placed under the footing, in which the lower two layers are connected by both sewing the bottoms and tying together the openings of two bags and the upper two layers are connected by tying the openings of two bags.

Fig. 30. Typical arrangement of soilbags for reinforcing soft building foundation with N -values as low as 1~2

Under the whole raft foundation, two layers of soilbags (not connected) are placed (Fig. 31(b)). The used soilbag usually has a size of about 40 cm long by 40 cm wide by 10 cm high. The materials inside the soilbag that we have used are crushed stones, excavated soils, asphalt wastes and waste tiles. The bag is usually made of polyethylene that does not deteriorate for a long time because it is embedded into the ground and thus protected from sunlight. During construction, every layer of soilbags are well compacted with vibrators to reduce the deformation of soilbags before the soilbags take effect when they are subjected to external forces from the buildings.

To elucidate the effectiveness of this reinforcement method, we estimated the bearing capacity of the soft ground with a soilbag arrangement as shown in Fig. 30. Since soilbags have very high strengths, more than 1.4 MPa from Table 1, it was assumed that the soilbags would not be broken under the usual upper building load. Furthermore, as a large apparent cohesion (about 270 kPa under the vertical load calculated by Eq. (3) with the soilbag parameters of $T=12$ kN/m, $\phi=44^\circ$, $B=40$ cm and $H=10$ cm) is induced in the soilbags due to the tensile force of the bags, the sliding failure would take place in the ground beneath the soilbags rather than

Fig. 31. Typical construction field of using soilbags to reinforce soft building foundation with N -values as low as 1~2: (a) soilbags under footing and (b) soilbags under raft foundation

(a) Waterlogged weak ground

(b) Arrangement of soilbags

Fig. 32. Waterlogged weak ground where soilbags were successfully used

inside the assembly of the soilbags. The soilbags in Fig. 30 are considered to take effect successively as follows: ① The 3 lowest soilbags beneath the footing take effect firstly under the upper building load; ② The 4 lowest soilbags and those in the side of the footing come to be effective as the settlement of the footing develops; ③ As the settlement becomes larger, all the soilbags under both the raft building foundation and the two footings (In real construction fields, there are another same footing and the soilbag arrangement that are not shown in Fig. 30) surround and confine a part of the ground below the raft building foundation, constituting a larger and deeper reinforcement body for the ground. Herein, we take only the 3 lowest soilbags beneath the footing into account and their contributions are considered to result from the widening and deepening of the footing. The effective width of the soilbag assembly is assumed to be 120 cm, the total width of the 3 lowest soilbags just under the footing. The depth of the soilbags beneath the footing is considered to be 40 cm, the total height of the 4 layers of the soilbags. The extremely soft ground is considered to have the soil properties of $\gamma_t = 16 \text{ kN/m}^3$, $c = 10 \text{ kPa}$ and $\phi = 0^\circ$. The width of the building footing is considered to be 40 cm and the depth of the ground above the footing is assumed to be 20 cm. Under these conditions, the bearing load of the ground per unit length of the footing is calculated to be 21.84 kN/m

before the reinforcement with soilbags and 73.2 kN/m after the reinforcement with soilbags. The bearing load after the reinforcement by soilbags is 3.35 times larger than that before the reinforcement, which thus illustrates the effectiveness of the soilbags to reinforce soft grounds.

In the application of this method, we encountered an extremely weak foundation where the ground was waterlogged and a workman settled into it as deep as 30 cm, as shown in Fig. 32(a). In this case, 3 layers of 4-connected soilbags were first placed into the ground below water level, and then 5 layers of such soilbags were further placed above the ground water as shown in Fig. 32(b). The materials inside the soilbag were crushed stones. After the reinforcement, the ground can even withstand a heavy construction machine like backhoe (Matsuoka et al., 2000b).

Construction of Retaining Walls and Debris-Diversion Embankment with Soilbags

There have been several cases of constructing retaining walls using soilbags. Figure 33 shows one that was constructed on a loam foundation with a height of about 4.5 m, a total length of about 21 m and an inclined angle of 75° (Matsuoka et al., 2000b). Six soilbags are connected behind the wall in the lower part and 10 soilbags are connected in the upper part (Fig. 33(a)). One soilbag has a size of 40 cm in length by 40 cm in width by 10 cm in

(a) Arrangement of connected soilbags

(b) Completion of retaining wall

Fig. 33. Construction of a retaining wall with 30,000 soilbags consisting of waste tiles and polyethylene bags

(a) Soilbag arrangement

(b) Construction field

Fig. 34. Typical cross-section of debris-protected embankment constructed using large soilbags that consist of scoria and PP(UVR) bags in Miyake Island

height. The materials inside the bags are construction wastes with tiles that were free of charge. The bag is made of polyethylene. The soilbags are piled up and well compacted with vibrators layer by layer. Since the polyethylene bag is sensitive to sunlight, a thin layer of steel-reinforced mortar is cast on the outside surface of the wall, as shown in Fig. 33(b). In this project, about 30,000 soilbags were used and the construction was very silent because of no use of any heavy construction machines as used in pile driving.

Figure 34 presents the application of soilbags to construct a 436 m long embankment, which was used to divert the flow of volcanic mud and was carried out by Tokyo Metropolitan, in Miyake Island, Japan, where a large volcano erupted in 2000. In that project, a large-scale soilbag of 1 m long by 1 m wide by 20 cm high, which is made of polypropylene with a property of resisting against ultraviolet ray (PP(UVR)), was developed. The materials inside the soilbags are scoria of volcanic deposits that are now very difficult to get rid of in Miyake Island. Thus, soilbags provide an effective way of dispos-

ing these volcanic deposits. About 10,000 large-scale soilbags were used.

EFFECT OF REDUCING TRAFFIC-INDUCED VIBRATION

When reinforcing soft building foundations, soilbags have also an effect of reducing the traffic-induced vibration in addition to improvement of the bearing capacity. Herein, we present an example of the traffic-induced vibration measurement in a field (Matsuoka et al., 2000c).

The vibration measurement was taken in such a field where the traffic-induced vibration troubled the residents seriously before the house was rebuilt; and, this trouble was completely removed after the house was rebuilt with the foundation reinforced by soilbags. Figure 35 illustrates the locations of two measuring points. The measuring point P_2 is located on the 1st floor of the building where the foundation is reinforced with soilbags, while the measuring point P_1 is located on the ground close to

Fig. 35. Vibration measuring points

Fig. 36. Measured accelerations in z -direction: (a) no reinforcement and (b) with reinforcement

point P_2 but outside the building where the foundation is not reinforced with soilbags. The directions along and perpendicular to the traffic road are denoted as x - and y -directions, respectively. The vertical direction is denoted as z -direction. The measured accelerations at points P_1 and P_2 in z -direction are plotted against time in Fig. 36. Similar results are obtained in both x - and y -directions. It is clearly seen that the accelerations induced by traffic vibration at point P_2 are much smaller than those at point P_1 . Furthermore, Fig. 37 gives the relationship between the ratio of acceleration spectrum at point P_2 to that at point P_1 and vibration frequency in z -, x - and y -directions, respectively. It is seen that, within the vibration frequency ranging from 1 to 10 Hz, the acceleration spectrum at point P_2 decreases by less than half that at point P_1 (the ratio is about 0.4) in any of three directions. It is known that the vibration with a frequency ranging from 5 to 8 Hz is the most sensitive to human feeling and the resonance frequency of a wood-made house is less than 10 Hz. Thus, soilbags are very suitable to the reinforcement for foundations of houses.

The mechanism of vibration reduction by soilbags is still unclear. It may be contributed to the different

Fig. 37. Relationship between ratio of acceleration spectrum and frequency in x , y and z directions measured at points P_2 and P_1

stiffness of the solid soilbags with the surrounding soft foundation, causing loss of the vibration input, and the discontinuity of the soilbags, which absorbs the vibration energy or reduces the vibration.

EFFECT OF PREVENTING FROST HEAVE

Frost heave is a phenomenon where ground water freezes and causes an expansion of the ground in cold areas. It is harmful if there is a continuous supply of ground water, mainly due to capillary action. The conventional method of preventing frost heave is to deepen the concrete footings over the specified depth of frost heave, as shown in Fig. 38(a), which usually results in a long construction period and vast construction costs. Figure 38(b) presents a new method to prevent frost heave by using soilbags with coarse materials inside the bags. The soilbags are placed to the depth of frost heave. The number of layers, usually ranging from 2 to 6, is determined from the depth of the specified frost heave prevention and the bearing capacity of the ground. Since the soilbags with coarse materials inside the bags have large voids, it is difficult for the capillary water to rise into the soilbags or soil ground over the soilbags. Suzuki et al. (2000) carried out a frost heave prevention test by embedding soilbags into the ground under the depth of 20 cm. The ground consisted of volcanic ash clay and the material inside the soilbags was crushed stone with grain

Fig. 38. Methods of frost heave prevention in cold areas

sizes of 2.5 mm ~ 20 mm. It was found that the increase in water content in the ground of 20 cm above the soilbags was only 5%, suggesting that the capillary water hardly rose into the soilbags and thereafter the frost heave did not take place, while the increase in water content in the surface ground of 20 cm was as much as 20% without soilbags embedded in the ground. Thus, the effectiveness of preventing frost heave by soilbags with coarse materials inside the bags has been verified. So far, there have been several applications of this method in the Hokkaido area of Japan.

CONCLUDING REMARKS

Soilbags have been commonly used for a long time, but until now, very few studies have been made and very few applications have been reported except the use of them to prevent a flow of soil due to water. In this paper, the mechanical and the strength properties of soilbags were described in details, and many applications of soilbags in earth reinforcement are presented. Through our studies and real applications, many great advantages of soilbags have been found, which can promote increasing applications of soilbags in earth reinforcement.

The main results of this paper may be summarized as follows:

- 1) Soilbags take effect due to the tensile force of the bag when it is subjected to external forces that are the foundation *enemies*.
- 2) An apparent cohesion, c , is produced in soilbags due to the tension of the bag, which is the reason why the soilbag has an extremely high compressive strength. The apparent cohesion, c , decreases with an increasing angle between the external major principal stress and the normal of the longitudinal axis of the soilbag.
- 3) The materials inside soilbags can be any excavated soils as well as construction or naturally produced wastes, which provides us a promising and effective way of recycling wastes.
- 4) Reinforcing soft foundation by using soilbags can

have the effects of reducing traffic-induced vibration and preventing frost heave in addition to increasing bearing capacity.

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