Design and Analysis of Geo Wall
Based on ASCE Student Competition

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ABSTRACT: Geo wall is one kind of the common structure in the field of civil engineering, which is also named as reinforced retaining wall, and it is a particular one which is often applied in highway, railway projects and so on. In the United States, the geo wall competition is quite an important part of the ASCE student conference competition. In this competition, the structure of geo wall is simplified as a model consisting of post-board paper face, Kraft paper reinforcements and sand in a box. By participating in such game, students could learn more about geo wall structure and gain their own thoughts towards the calculation assumptions and methods which would even be applied into the real construction cases. In this paper, the author would combine the competition experience to expatiate the design assumption, method and experience and make a further analysis combined with soil mechanics and real engineering projects.

INTRODUCTION

Geo wall is one kind of soil reinforcement technology began in 1960s, which is proposed by the French engineer Henri Vidal after his series experiments. Because this kind of wall is easy to build, cheap and has a better prospect, it has been widely used in overseas transportation projects. In China, the design of subgrade structure in mountain freeway mostly adopts such method and it works well.

ASCE student conference holds student competitions every year including steel bridge, concrete canoe, geo wall and others. Among these competitions, the geo wall competition would require every team to use poster board to simulate the retaining wall facing use Kraft paper to simulate geosynthetic reinforcement and use a sandbox with three closed surfaces and one open surface to simulate the container, then set the reinforced sand wall into sandbox and test it with loads according to the rules. Finally, judgment will evaluate one team by a formula with its structure's mechanical performance and material cost. Luckily, the author participated in ASCE mid-pacific student conference geo wall competition in April 2013. As the following, the author will introduce this competition held in San Jose University, California and talk about some researches about the reinforced retaining wall based on such competition process and experience.

THE BASIC PROPERITIES OF GEO WALL

Reinforced retaining wall is composed of facing, reinforcements and backfill, and they would interrelate together to bear the lateral soil pressure. By adding reinforcements into soil, the structure could make full use of the friction between soil and reinforcement so that it improves both the deformation condition and engineering properties of soil which could make the wall facing keep erect or close to the upright. As a result, it improves the stability of whole structure.

SUMMARY OF THE COMPETITION

The reinforced retaining wall for the competition is to use tape to make Kraft paper reinforcements stick to the post board, and the goal of the structure is to use the least material to reinforce the soil for the vertical and horizontal loads according to the rules.

The competition is divided into two parts. The first part is fabrication and wall construction, and the second part is loading and scoring.

The fabrication part could be further divided into three steps: the first step, cutting Kraft paper to make the reinforcements; the second part, cutting the poster board to make the wall face and sticking reinforcements onto the face; the third step, erecting of the wall facing and then filling the sandbox with sand layer by layer.

The loading part could be divided into four steps: the first step, removing away the wood panel; the second step, loading the vertical load in the designated place; the third step, loading the horizontal load in the designated place; the forth step, loading the horizontal dynamic load. The scoring criteria would not be in detail in this paper.

The final result would be calculated by the formula with parameters like paper mass used, bearing capacity and wall face. So the question could be simplified as to calculate the object function about weigh of materials that could make the structure pass the loading steps. As a result, excluding the manual factors, the key of the competition is to choose the most economy reinforcement figure and the plan of reinforcement layout.

MATERIAL EXPERIMENTS

Before the design, the first step is to do some material experiments to get some key parameters of the reinforced retaining wall, like density of the sand, tensile strength of the reinforcement and so on.

(a) Tensile test (b) Pullout test (c) Connection strength test

Fig. 1. Experimental test

As for soil, its tensile strength is almost negligible. However, the soil reinforced by reinforcements could withstand a certain tension. Therefore reinforcement should have great initial tensile modulus and tensile strength when the reinforcement has a small elongation. We adopted tensile testing machine (see fig.1 (a)) to measure the tensile strength of the reinforcement and got the longitudinal (paper fiber direction) tensile strength.

As shown in fig.1 (b), fifteen pullout tests were performed under different normal stress provided by airbags. Four normal stresses ranging from 20 psf to 100 psf were considered in the tests, and we got the soil-paper interaction friction angle.

Connection strength tests were conducted on a ten inch long and four-inch wide piece of paper strip, which was connected to the poster board with tape of the same width (see fig.1 (c)). The maximum of the tensile load was recorded. All parameters used in the design of Geo wall are listed in table 1.

Table 1. Material Properties

Item	Value	Unit
Unit weight of sand	100	pcf
Friction angle of sand	33.8	degrees
Paper tear strength (reinforcement)	22.9	lb/in
Interaction friction angle	35	degrees
Connection strength	14.7	lb/in

DESIGN METHODS

The Principal of the Reinforcement Retaining Wall

Sandy soil could easily lead to a serious deformation, or even collapse under its weigh or external forces. If there exist flexible reinforcements along the tensile strain, friction would be produced between reinforcements and soil, which makes soil "possess" a certain degree of cohesion, so as to improve the mechanical properties of soil. We often use following theories to explain above phenomenon: the interface friction theory, confinement theory.

Failure Modes of the Reinforced Retaining Wall

For the reinforced retaining wall in the real world, the failure modes could be classified as follows:

a. External failure mode: reinforced soil keeps the overall movement, according to its cause and way of failure and deformation it could be further divided into horizontal sliding, overturning, failure of foundation and deep sliding failure.
b. Internal failure mode: because of the interaction between soil and reinforcements, it could be divided into reinforcement pullout failure and reinforcement breakage.
c. Failure mode with facing: due to the stiffness of facing and the strength of connection, it could be divided into face-reinforcement connection failure, face buckling and so on.

According to the questions in the competition and materials provided by the host (sandy soil, poster board and Kraft paper), the failure could be concluded as following categories:

1. Face-reinforcement connections fail. The failure point would be at the connection point.
2. Break of reinforcement. The failure point at the middle of the reinforcements.
3. Face buckling. It would lead to leakage of sand, resulting in overall deformation failure.

Layout Design

According to above theory, we should determine different plans corresponding to different failure modes. First, we might do the layout design to determine the location and number of reinforcements.

Comparing with materials tensile strength, stiffness between real engineering project and model structure, we got some new ideas and obtained two simplified plans: rigid plan and flexible plan.

We assume that the mechanism of the geo wall could be different in several areas with different reinforcement density. When the density of reinforcements is quite high, it could be seen as that external force is mostly beard by reinforced soil, the reinforcing material will confine the soil well and the face only bears little part, so the face could be seen as no deformation. When the force exceeds the ultimate tension of reinforcement, the reinforcement would break and the structure would suddenly collapse. This is defined as the rigid plan.

When the density of reinforcements is low, the face would bear a certain part of force. Then when soil has a relative displacement, the face would buckle at the corresponding place where soil is loose and has displacement. It's likely that the face might through such buckling deformation to obtain a new equilibrium or lead to a continuous sand leakage until the structure collapses, and we call it the flexible plan.

We think that rigid plan will exhibit a brittle failure with little redundancy of deformation. As a result, reinforcements are broken leading to a sudden collapse. On the contrary, flexible plan has some redundancy of displacement and the structure would not collapse suddenly; instead, it would charge distribution force to obtain a new equilibrium by deformation of each time. Compared with the rigid plan, the flexible plan has certain ductility. But for the contest, flexible plan might appear a large deformation which would lead to score deduction or even disqualification.

Through the control of number and spacing of reinforcements, the rigid plan or flexible plan were tried separately. However, because of the heterogeneity of soil, two plans are often intercrossed, yet we still could distinguish them from extreme ways. In order to avoid the weak area that might appear, software was used to simulate the reinforced soil wall and we knew that it could have an effect of mutually constrain and support to limit the displacement and deformation, as long as reinforcements were settled as rectangular ($2\ inch \times 2\ inch$) uniformly and staggered up and down.

According to Bilgin,Ö.(2009), internal friction angle of reinforced soil would have great influence on the deformation. As the internal friction angle increased form 30° to 42° (common sandy soil's angle)，the most large deformation would reduced by 50%, and vice versa. Therefore, according to the sand provided in the competition, we could measure the internal friction angle and then choose the most appropriate plan.

Facade Design

After determining the layout, the next step is to determine the length of reinforcements. The core idea is the establishment of limit equilibrium equation.

Firstly, we introduced three key assumptions:

a. The design is a three-dimensional problem, and we just regard it as a plane-strain problem, not considering the boundary effect.
b. According to *NHI Courses No.132042 and 132043* and referring to Ye (2010), the slip surface we used is presented as fig.2.
c. There is no displacement for the wall.

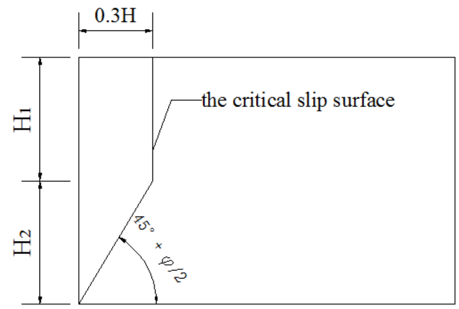

Fig.2. The critical slip surface

Load Simplification and Calculation

1. Earth pressure calculation (only backfill)

$$\sigma_a = K\gamma z \tag{1}$$

$$P_a = K\gamma H^2/2 \tag{2}$$

$$K = tan^2(45° - \varphi/2) \tag{3}$$

where: $\sigma_a =$ the lateral earth pressure at the depth of z; H= the height of the wall; $P_a =$ the overall lateral earth pressure; $K =$ Rankine active pressure coefficient

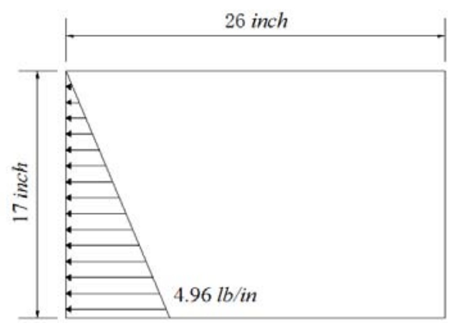

Fig.3. Earth pressure

2. Earth pressure caused by vertical surcharge load

When determining the effect of vertical load, we separately analysed it from front elevation and side elevation. Because the area of vertical surcharge load was only the area of the bucket bottom, we applied the stress dispersion method so that the model structure would be more close to the real stress condition.

By simulation and reference to stress dispersion, we got the calculation model of stress dispersion shown as fig.4 and fig.5.

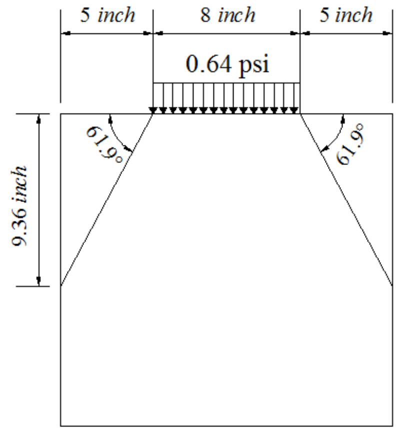

Fig.4. Front elevation view

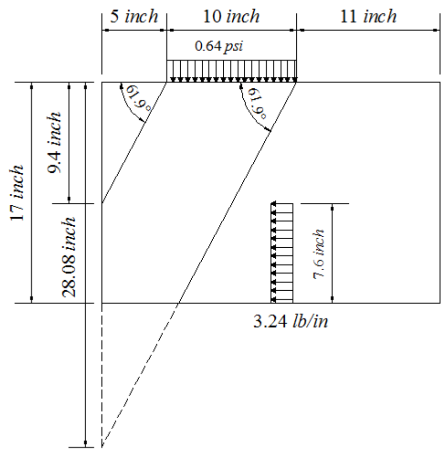

Fig.5. Side elevation view

It could see that only the region within 7.64inch over the bottom of the earth wall would be influenced by the vertical load.

3. Earth pressure caused by lateral load

Third and fourth step both are horizontal load. The vertical load would be transformed into horizontal load by means of a loading frame as below.

Fig.6. The loading pattern

In the calculation, we assume that there is no displacement of the standpipe at the bottom, which means that it could be seen as a pivot point. The moment on the top is caused by vertical load around the standpoint will be resisted by lateral force of side soil, and the force is in a triangular distribution along the whole pipe as shown by fig.7.

After we get the total force the pipes exert, and then disperse the force towards the panel (refer to fig.8).

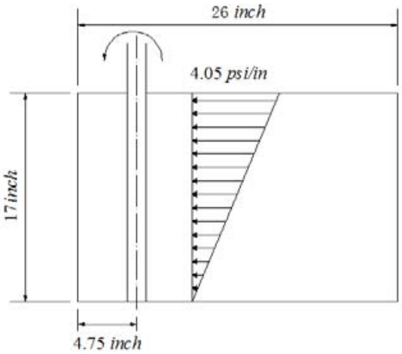

Fig.7. Front elevation view

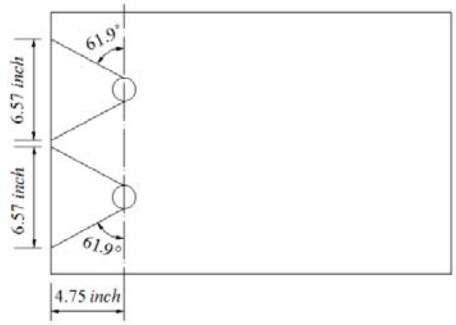

Fig.8. Side elevation view

Finally, by superposition of stress caused by vertical and horizontal loads, we could get the final stress on the face and finish the calculation of reinforcement tension and geo wall design.

4. Determination of reinforcement

Considering the adverse effects of large deformation, we finally adopt the rigid plan. Moreover, considering the spacing of reinforcements is mainly based on the position of PVC pipes, the location of reinforcements near the pipes would be adjusted slightly in order to avoid the inconvenience in construction. In addition, the location of reinforcement has a better effect in uniform than not.

According to the load calculation under above load condition, we could calculate the length of the reinforcement by referring to Xu and Xing (2010).

$$L = L_1 + L_2 + L_3 \quad (4)$$

where: $L_1 =$ the anchorage length, $L_2 =$ the length in the failure wedge, and $L_3 =$ the length for attachment to face, $L_3 = 1\ inch$.

$$L_{1i} = T_i/(\alpha \cdot b_i \cdot \sigma_{zi} \cdot F \cdot c) \quad (5)$$

$$T_i = \int_{S_v} \sigma_x \, dS_v \quad (T_i < Min(T_{element}, \ T_{tape})) \quad (6)$$

where: $T_i =$ the force that the i_{th} row bears, , $T_{element} =$ the strength of element, $T_{\mathrm{tape}} =$ the strength of tape, $b_i =$ the width of i_{th} row reinforcements, $S_v =$ the vertical reinforcement spacing, $S_H =$ the horizontal reinforcement spacing, $\sigma_{zi} =$ the vertical earth pressure on the position of the i_{th} row, $\alpha =$ scalecorrection factor, should be 1, $F =$ resistance factor for soil reinforcement pullout, $c =$ factor for strip type reinforcement, should be 2, and the length of L_2 is based on the critical slip surface in fig.5.

$$\mathrm{z} < 7.45, \ L_2 = 5.1; \ \mathrm{z} > 7.45, \ L_2 = (17 - \mathrm{z}) \times 5.1 \times \tan 61.9° \quad (7)$$

Final Design

Through above calculation, we obtained the result. However, considering that the actual model is three-dimensional and other factors, we need to modify the result like construction convenience, effect of standpipe, boundary effect, environmental humidity and sand accidental equivalent water content, dynamic load amplification and so on. Finally, our design was as below, and the estimated mass of reinforcements was 4.5g

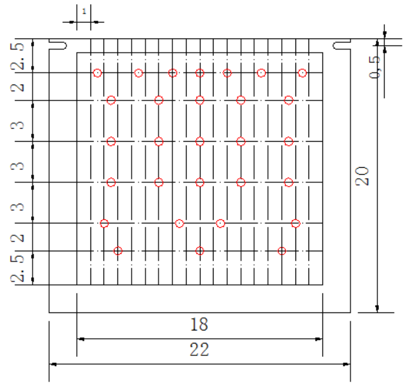

Fig.9. The layout of reinforcement

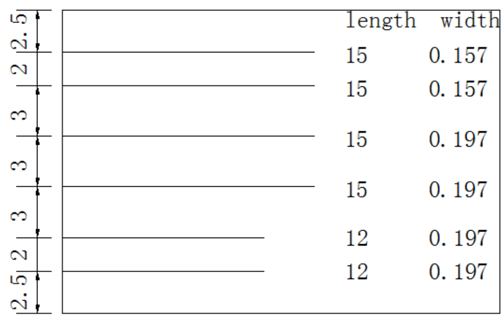

Fig.10. The dimension of reinforcement

We might use mass of reinforcements to represent the reinforcement density. Through the contrast experiments we found that there existed a relationship between bearing capacity, failure modes of wall and the reinforcement mass used. When the reinforcement mass was less than 4.0g, the wall demonstrated flexibility, while the mass was more than 4.5g, the wall would bear more loads and collapse suddenly, showing rigid characteristics. In the case of reinforcements mass between 4.0g to 4.5g, it might either be flexible plan or rigid plan, so it is hard to estimate the failure mode and optimize the plan. As a result, we choose 4.5g reinforcements as a rigid plan that is the least weight of this plan; therefore, it would make sure that the structure will be in the failure mode of rigid plan.

DETAILINGS

In fact, the model and real engineering project often complement each other, and some complicated situations that could not be simply treated could be ensured by structural measure.

In real reinforced soil wall or steep slope projects, we often adopt geosynthetics as reinforcing material, especially the geogrid. Therefore, when we choose reinforcements in the contest, linear Kraft paper strip is not necessary, even the punched paper similar to the structure of geogrid can be used. In theory, the hole could hoop certain parts of soil so as to limit the displacement and do good to control the deformation of the structure.

By assumption, we think reinforced soil should be as denser as possible, and compactness of the backfill does not play a key role towards the reinforcements. However, actually according to the theory of Swami Saran，K.G.Garg and R.K.Bhandari (1992), the compactness of backfill would be closely related to the bearing capacity. In fact, the backfill could bear a certain part of surcharge load and play the role of limiting the displacement of reinforced soil. Therefore, the denser the backfill, the better it do to the bearing capacity of structure.

CONCLUSION

Through design and construction of the reinforced retaining wall, students could fully apply the plain knowledge in textbook into practice, and fully aware of the structure form and characters of geo wall so as to improve the professional knowledge. Through theoretical modelling and practical engineering analogy, it might a major advantage of modelling analysis to find the structure key point, details requirements and even put some new phenomenon as feedback in the actual project.

Our team participated in 2013 ASCE mid-pacific student conference geo wall competition and got the sixth place. Out of the game, I often think about the advantage and disadvantage of our design. I see that USA teams are rich in new designs and their students take the competition as a kind of enjoyment and fun. Therefore, they will often come out some new and efficient designs that we might not just by traditional methods. As a result, as a civil engineer, when we maintain a rigorous mind, we also need to frame out of thinking. So some kinds of newly-type, reasonable and efficient design would come into being just in such brainstorm and free imagination.

Recently, driven by the competition held in the USA, there also arise some competitions like geo wall competitions for domestic undergraduate and even middle, I think these activities would promote to produce more innovative excellent engineers in the future.

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