Influence of Aggregate Thickness and Reinforcement Depth on Deformation Behavior of Geogrid-Reinforced Layer

AUNG AUNG SOE¹, Jiro KUWANO², Ilyas AKRAM³ and Takaya KOGURE⁴

The deformation potential of geogrid-reinforced aggregate layer was investigated through laboratory large scale model tests. The influence of the aggregate layer thickness was mainly considered together with reinforcement depth. Cyclic pressures were applied with increasing the amplitude after every 500 cycles. Under low pressure amplitude, the rate of surface deformation reached a stable stage with increasing load cycles, regardless of reinforcement condition. This rate was more progressive with load cycles under high pressure amplitude, which was more obvious in unreinforced case. Surface deformation was considerably resulted from lateral flow in thick aggregate layer, and from subgrade deformation in case of thin aggregate layer, especially for the reinforced case. The contribution of subgrade deformation was small on surface deformation in thick aggregate layer, while it was significant in thin layer. The effective reinforcement condition was achieved when geogrid was placed at the middle of layer.

KEYWORDS: Cyclic Loading, Pressure amplitude, Deformation, Geogrid, Aggregate layer

1. Introduction

Flexible pavements play an important role for the inland transportation purpose. Depending on the traffic volume and location, flexible pavements are usually designed as the paved or the unpaved ones. In flexible pavement, there usually includes four distinct layers¹⁾: (1) asphalt concrete, (2) base course (aggregate layer), (3) subbase, and (4) subgrade (existing soil). Flexible pavements are designed so that the load from vehicle tyres safely transfers through the structural layers to the subgrade layer. For this purpose, structural layers, especially base course, have to be maintained their thickness during design life of pavement.

Since geosynthetic materials have been introduced, they were used in many geotechnical applications, such as foundation, retaining wall, embankment and pavement. Depending on the applications, several types of geosynthetic materials have been developed, for example: geocell, geomembrane, geotextile, and geogrid. Among them, geotextile and geogrid are mainly used for the reinforcement purpose in flexible pavement.

For geotextile, the key functions in improving flexible pavement are separation, reinforcement, and filtration²⁾. For geogrid, reinforcement mechanisms can be distinguished into lateral restraint, improved bearing capacity and tensioned membrane effect³⁾. Among them, lateral restraint or confinement can be regarded as the primary reinforcement mechanisms of geogrid⁴⁾. With this confinement effect, the lateral shear flow can be reduced within the base course layer.

The characteristics of geogrid-reinforced pavement have been studied by many researchers^{2), 5), 6)}. These studies included the laboratory triaxial test, large scale test, field test and numerical simulation. These studies reported the

potential benefits of geogrid reinforcement, such as the reduction in permanent deformation and the improved mechanical behavior. However, it is still needed to understand the reinforcement behavior due to varying test conditions such as geogrid type, material type and so forth. In addition, the cyclic pressure was usually considered as constant in the previous studies. In reality, however, the applied repeated traffic load on the pavement structure may vary with the vehicle type. Therefore, it becomes necessary to know the behavior of flexible pavement under variable load intensities induced by different vehicle types. In the current study, the deformation behavior of geogrid-reinforced unpaved road was investigated, considering aggregate base course thickness and reinforcement depth under the varying amplitudes of cyclic pressure.

2. Experimental program

In this study, six cyclic plate loading tests were conducted, including three geogrid-reinforced tests and three no-reinforced tests. In no-reinforced tests, three base course thicknesses were modelled as 10 cm, 20 cm and 30 cm. In the geogrid-reinforced tests, two base course thicknesses were considered as 10 cm and 20 cm, in which geogrid was placed at the boundary between subgrade and base course. In another reinforced test, geogrid was laid in the middle of 20 cm thick base course layer. Test conditions are presented in Table 1. In each test, cyclic load was applied starting from 100 kPa to 400 kPa, with 100 kPa increment. Under each pressure level, cyclic load was allowed to apply until 500 cycles. In this test program, the failure condition was considered when surface settlement reached 30 mm which is the allowable rut depth

^{1,3,4}Student Members of JGS, Graduate Student, Graduate School of Science and Engineering, Saitama University

²International Member, Graduate School of Science and Engineering, Saitama University

that develops under construction traffic, specified in Design Guidance for Road Pavement Foundations (Interim Advice Note)⁷⁾.

Table 1. Test conditions

Reinforcement	Thickness (cm)		Geogrid Position
	Subgrade	BC*	
No	63	10	-
	53	20	-
	42	30	-
Geogrid	62	10	At bottom
	52	20	At bottom
	53	20	At middle

*BC = Base Course

3. Materials

3.1 Subgrade and Base Course

In order to model the subgrade and base course layers, silica sand No.5 and No.1 were selected for the large scale model study. Subgrade was modelled by using fine silica sand No.5. The index properties of this sand are: specific gravity $G_s = 2.675$, average particle size $D_{50} = 0.488$ mm, coefficient of uniformity $C_u = 1.98$, coefficient of curvature $C_c = 0.943$, maximum dry density $\rho_{\max} = 1.628$ g/cm³, and minimum dry density $\rho_{\min} = 1.338$ g/cm³. Silica sand No.1 was used to model the aggregate base course layer. This sand was selected because it is the largest available sand on the market and its average particle size is larger than the rib thickness of the geogrid used. Since it is a uniform coarse sand, the variation of base course layer in each test can be minimized during preparation. This sand has the following indexes: average particle size $D_{50} = 3.735$ mm, $C_u = 1.904$, $C_c = 0.879$. Since C_u and C_c of both sands are not in the range, $C_u > 6$ and $1 < C_c < 3$, specified by Unified Soil Classification System (USCS), these sands are regarded as poorly graded sands (SP). The particle size distribution curves are shown in Figure 1.

Figure 1. Particle size distribution curves of subgrade and base course

3.2 Reinforcement Material

Triangular geogrid, TX160, was selected for the reinforcement of the aggregate base course layer. This geogrid was recently developed by Tensar. The tensile strength of geogrid is 10 kN/m. The unit weight is 245 g/m² and junction thickness is 3.1 mm. The dimension of this geogrid is shown in Figure 2.

Figure 2. Dimensions of triangular geogrid

4. Experimental setup and testing procedure

In this experimental study, a large square tank, 100 cm x 100 cm x 80 cm, was used for the preparation of model pavement tests. A rigid circular steel plate, diameter of 17.5 cm, was used to simulate the traffic load because it was assumed that the wheel load would be radially distributed over the base course layer. Since the total depth of subgrade and base course was greater than 70 cm in each test, the boundary influence of the tank base would be negligible according to Boussinesq Stress Distribution Analysis. In addition to this, the influences from the tank walls would be minimal on the test data because the size ratio between tank and footing diameter is considerably large ($100/17.5 \approx 6$)⁸⁾⁹⁾.

In each test, subgrade layer was prepared by using sand raining method¹⁰⁾¹¹⁾¹²⁾. By using this method, the relatively high densities of the subgrade layer were achieved between 1.54 g/cm³ to 1.66 g/cm³, which were average densities calculated from the attained thicknesses. After the subgrade layer reached to the desired level, a small plate was placed at the predetermined location. Then, a small tube was set above that plate, through which it was able to monitor the subgrade settlement. Then, the base course was prepared by manual compaction. In each lift, 80 kg mass of aggregate was used. The compaction was done until the average thickness of the aggregate layer became 5 cm. Hence, the average density of base course was 1.6 g/cm³ in each test.

The rigid circular plate was set after the preparation of subgrade and base course layers. A linear variable displacement transducer was set on the footing to monitor surface deformation, which was set as close as possible to the loading arm. Another transducer was used to monitor subgrade deformation through the small tube, which was at the fixed point 4.5 cm from center. To simulate trafficked loading, a trapezoidal load pulse with a frequency of 0.1 Hz was applied with the help of a function generator, Electro-Pneumatic (E-P) transducer and pneumatic pressure via Bellofram cylinder. In each

test, cyclic load was applied with variable amplitudes ranging from 100 kPa to 400 kPa. Each loading step was allowed to apply for 500 load cycles. Load variations and deformations of the surface and subgrade were recorded by the data acquisition system at every 1 second. The configuration of test setup is shown in Figure 3.

Figure 3. Layout of test setup

5. Results and discussion

5.1 Influence of aggregate thickness on the deformation of no-reinforced layer

Three tests were performed with different base course thicknesses: 10 cm, 20 cm, and 30 cm. From each test, permanent surface and subgrade deformations (settlements) were taken when the footing pressure was minimum in each cycle. These deformations are presented in Figure 4.

As seen in Figure 4a, the surface deformation of 10 cm thick aggregate base course is obviously larger than those of other cases under same pressure level. Under 100 kPa pressure, 10 cm thick case reached the permanent deformation of greater than 5 mm, within few load cycles. On the other hand, 20 cm and 30 cm cases deformed about 3 mm after the same load cycles. After 300 cycles under 100 kPa, the incremental permanent deformations became negligible in all cases. Under 200 kPa, however, the surface deformation of 10 cm case dramatically increased with load cycles until 500 cycles. This drastic surface deformation was mainly resulted from the base course deterioration and the deformation of subgrade layer, shown in Figure 4b. This was because, under 200 kPa pressure, the lateral flow of aggregate materials would have been occurred within base course layer and the strains in this subgrade layer might have reached the plastic deformation state, so called ratcheting zone^{13), 14)}, because the subgrade layer deformed with a constant accumulation with load cycles as shown in Figure 4b.

Figure 4. No reinforcement: (a) surface and (b) subgrade deformations

For 20 cm and 30 cm cases, the rates of surface deformation slowed down with load cycles. However, the stable stages were not observed till the end of 500 cycles. Though base course thickness increased from 20 cm to 30 cm, their surface deformations were almost same under 100 kPa and 200 kPa pressures. In these cases, the aggregate particles might have been densified under 100 kPa because the respective subgrade deformations were negligible small. In addition, obvious surface bulging was not noticed under 100 kPa in these cases. However, the aggregate particles were mainly driven out by the lateral flow action under 200 kPa, showing visible surface bulging. This can be explained from the subgrade deformation behavior, as seen in Figure 4b. The subgrade deformations of these cases are almost same under 100 kPa. However, the subgrade deformation of 30 cm section is smaller than that of 20 cm section under 200 kPa. Due to the progressive lateral flow of aggregates under 200 kPa, this resulted in the reduction of aggregate layer thickness. Consequently, this would increase the stress intensity on subgrade layer. Hence, the larger deformation was observed in the subgrade layer of 20 cm case. The subgrade deformations reached their stable stages within few cycles under 200 kPa, while the surface deformations were still increasing with load cycles. This implied that the lateral flow process continued with increase in load cycles. When footing pressure was further increased to 300 kPa, the sudden failure was found in 10 cm thick case.

This was due to the failure of subgrade layer, of which bearing capacity would be less than 300 kPa. On the other hand, the progressive surface deformations were noticed in 20 cm and 30 cm cases. Meanwhile, their subgrade deformations were increasing with slow rates. The rapid rates of surface deformation would have been contributed by the progressive rate of lateral flow, occurred inside these 20 cm and 30 cm thick base course layers. Unlike under 200 kPa pressure, surface deformation of 20 cm case was larger than that of 30 cm case under 300 kPa pressure. Because of higher stress intensity on subgrade layer, the subgrade deformation increased with load cycles in 20 cm case. This increment would also result in the larger surface deformation of 20 cm section. When pressure was increased to 400 kPa, the sudden failures were found in both 20 cm and 30 cm cases. Unlike 10 cm case, these sudden failures were mainly resulted from lateral flow of aggregate particles in those sections.

5.2 Influence of aggregate thickness and reinforcement depth on the deformation of geogrid-reinforced layer

Three geogrid-reinforced tests were conducted with two different base course thicknesses, 10 cm and 20 cm, in which geogrid was placed at the bottom of base course in one test and at the middle in the another test. The surface and subgrade deformations are shown in Figure 5.

As seen in Figure 5a, the surface deformation in 20 cm geogrid-reinforced case was largest among all cases under 100 kPa pressure. This might be due to the slightly lower density of this test section, which might have been occurred in the manual compaction process. After 200 cycles, a stable behavior was observed under 100 kPa pressure in all cases. With the increase in pressure until 400 kPa, the similar surface deformations were observed between 20 cm case and 10 cm case. Both cases suddenly failed after few cycles of 400 kPa. Although surface deformations were similar, the subgrade deformation of 20 cm case was considerably small, compared to 10 cm case, shown in Figure 5b. Regarding surface deformation, the ratcheting behavior under 200 kPa and the progressive plastic strain development under 300 kPa were recognized in 10 cm and 20 cm cases. However, these surface deformations were mainly contributed by the subgrade deformation in 10 cm case, and by the lateral flow of aggregate in 20 cm case.

Since the lateral flow type failure was observed in 20 cm test case, another test was conducted by placing the geogrid at the middle of 20 cm thick aggregate layer. As expected, the significant improvement in surface deformation was noticed under all pressure levels. Under each cyclic pressure, the increment of surface deformation was a bit slower than those of other cases with the increase in load cycles. This means that the development of lateral flow within the aggregate layer was effectively reduced by the confinement action on both sides of geogrid. Although 10 cm and 20 cm cases failed within few cycles under 400

Figure 5. Geogrid-reinforcement: (a) surface and (b) subgrade deformations

kPa, the 20 cm (geogrid at mid-depth) case withstood over 400 cycles. However, the progressive failure was also observed in this case under 400 kPa. This was because the lateral driving stresses induced from the applied 400 kPa pressure might exceed the confining strength, provided by the geogrid at mid-depth.

When the subgrade deformations of 20 cm and 20 cm (geogrid at mid-depth) cases were compared as shown in Figure 5b, it was found that the deformation of 20 cm case (geogrid at bottom) was smaller than that of geogrid at mid-depth case. This was obvious under 200 kPa and 300 kPa pressure levels. In 20 cm (geogrid at bottom) case, the stresses on subgrade layer might have been reduced by the geogrid, resulting in the smaller subgrade deformation. On the other hand, the applied stresses would have been allowed to transfer to the lower layer in the 20 cm (geogrid at mid-depth) case. Schuettelpelz et al.⁶⁾ reported that when geogrid position is close to the surface, this may allow the shear stresses to propagate below reinforcement. Due to this action, the stress intensity might increase on the subgrade layer of 20 cm (geogrid at mid-depth) case, resulting in the larger deformation. However, the stress intensity would be smaller than the bearing resistance of subgrade layer because bearing failure was not found in subgrade layer, like in 10 cm case. Hence, the mid-depth reinforcement section could effectively reduce the lateral shear flow of aggregate particles, meanwhile it could also transfer the safe stress level to the subgrade.

5.3 Contribution of subgrade deformation on surface deformation

The contribution of subgrade deformation on the surface deformation was calculated based on the measured deformations of surface and subgrade. This contribution is simply the percentage of the subgrade deformation (S_g) over the surface deformation (S_f). The average values were calculated under each pressure level, as shown in Figure 6.

As seen in Figure 6, the subgrade contribution is minimal in the thick base course layers: 20 cm-No, 30 cm-No, and 20 cm-Geogrid. Under the given pressure, the contribution is smallest in 30 cm case, followed by 20 cm geogrid-reinforced case and 20 cm no-reinforced case. This implied that the stresses at the subgrade level was reduced with the increment of aggregate layer thickness, and with the inclusion of geogrid reinforcement. In these cases, the increasing tendencies of the subgrade contribution was noticed with the increase in pressure until 300 kPa. Then, these cases showed the sudden failures under 400 kPa, due to lateral flow of aggregates. In case of 20 cm geogrid at mid-depth, the contribution values were larger than those of counterpart cases (20cm-No & 20cm-Geogrid). The trend increases from 100 kPa to 200 kPa, followed by the decreasing tendency with increasing pressure. This was because the stress intensity on subgrade layer increased when pressure increased to 200 kPa in 20 cm geogrid mid-depth case. When the pressure was further increased to 300 kPa and 400 kPa, the lateral flow of aggregates would have dominated in the aggregate layer. This resulted in the greater surface deformation rate, rather than the rate increase in subgrade deformation due to stress increment. Therefore, the contribution of subgrade became smaller under high pressure levels.

In 10 cm thick cases including both no reinforcement and geogrid reinforcement, the contribution percentages are greater than those of thick sections. In the no-reinforced case, the values increased from 32 % to 40 % when pressure changed from 100 kPa to 200 kPa. This was obviously due to stress increment on subgrade layer. Because of thin aggregate layer, the lateral flow potential of aggregates would be small in 10 cm thick case. Instead, the applied stresses would mostly concentrate on the subgrade. Consequently, the subgrade deformation became progressive and, hence resulted in the larger contribution on surface deformation.

For 10 cm thick geogrid-reinforced case, the largest contribution values of subgrade were observed under each pressure level. Interestingly, the percentage drop from 70 % to 60 % was noticed in this case while there were increasing trends in other cases, when the pressure increased from 100 kPa to 200 kPa. Under 100 kPa pressure, the aggregate layer would have been densified and this would allow aggregate particles to strike through the apertures of geogrid within first few load cycles, before reinforcement action could not be fully mobilized. This could cause the development of subgrade

Figure 6. Percent contribution of subgrade deformation on surface deformation

deformation. When reinforcement action started mobilize, the aggregate layer would become stiffer and the applied stresses would be widely distributed over the subgrade layer. In addition, the lateral driving stresses induced by 100 kPa pressure might be smaller than that of confining stresses provided by geogrid. Hence, the surface deformation was mainly contributed from subgrade deformation under 100 kPa pressure. Though geogrid could provide confinement to the aggregate layer, it would not be possible to fully confine the whole thickness. When the pressure increased to 200 kPa, the lateral driving stresses would also increase, and this would result in the development of the lateral flow of aggregates. Therefore, the contribution of subgrade deformation was reduced on the surface deformation with the development of lateral flow. Under 300 kPa, the contribution of subgrade deformation was almost constant. This means the rate of subgrade deformation increase and the rate of lateral flow development were same as those under 200 kPa pressure. Unlike no reinforcement case, this geogrid-reinforced case could withstand the whole 500 cycles under 300 kPa pressure, since the geogrid layer reduced the applied vertical stresses on subgrade layer. Under 400 kPa, the failure of section was observed because of bearing failure of subgrade layer.

6. Conclusions

The deformation behavior of aggregate layer was investigated considering base course thickness and geogrid depth. Six cyclic loading tests were performed. From the results obtained in this study, the followings can be concluded: 1) Regardless of reinforcement condition, the rates of surface and subgrade deformations reached their stable stages within few load cycles under low pressure amplitude. 2) With increasing pressures, the deformations increased with load cycles in all cases, and the rates were smaller in the geogrid-reinforced cases. 3) Surface deformation was mainly contributed by subgrade layer in 10 cm thick case, especially geogrid-reinforced case, while it was mainly resulted from lateral flow of particles in the thick aggregate layer. 4) This lateral flow potential is higher in the thick aggregate layers under high

pressure amplitudes, regardless of reinforcement condition. 5) It was observed that the geogrid at mid-depth reinforcement is effective to reduce the lateral flow potential of aggregates under high pressure and this could also transfer the safe stresses to the subgrade layer. 6) Under the given pressure, the contribution of subgrade deformation is significant on the surface deformation of thin aggregate layer. 7) With geogrid reinforcement, the reductions in surface and subgrade deformations were observed in 10 cm thick case. However, this was insignificant in 20 cm (geogrid at bottom) case.

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繰返し荷重振幅がジオグリッドで補強された骨材層の変形に及ぼす影響

Aung Aung Soe ・ 桑野 二郎 ・ Ilyas AKRAM ・ 小暮 峻矢

繰返し荷重振幅がジオグリッドで補強された路盤のような骨材層の変形に及ぼす影響をほぼ実スケールの室内模型実験で調べた。繰返し荷重は1段階500回載荷し、荷重振幅を段階的に増加させた。荷重振幅が小さい段階では、地盤補強の条件によらず、変形量は各荷重振幅で500回の載荷の間にほぼ定常状態となった。荷重振幅が大きく、ジオグリッド補強が無い場合はある場合よりもより顕著に、変形の増加が著しかった。骨材層の厚い場合は、砂で作製した路床部（下部層）の変形は地盤表面の変形にはあまり影響しないが、薄い場合は大きく影響する。地盤表面の変形は、路盤部に用いられた骨材層厚が厚いほど、またジオグリッドで補強されているほど、抑制された。

キーワード：繰返し載荷、荷重振幅、変形、ジオグリッド、骨材層