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学 位 論 文 題 目	Confined-Reinforced Subgrade to Reduce Differential Settlement of Road Pavement（道路舗装の不同沈下を軽減するための拘束補強路床）
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論文の内容の要旨

Earthquakes often induce differential settlement between bridge abutments and their approaches. Consequently, vehicles cannot pass the stepwise settlement created by the earthquakes. Geosynthetic reinforced soil has been widely used to mitigate such damage from earthquakes. Furthermore, one important aspect of reinforced-soil is its potential to reduce differential settlement. The confined-reinforced earth (CRE) method, has been proposed to make it possible for vehicle, especially emergency vehicles to pass road surfaces roughened caused by earthquakes. The CRE method employs geogrid layers, prestressed steel tie rods, and granular soil applied to subgrade layers under pavements of roads. In this study, a physical model, which can simulate a large-scale model of CRE but with smaller size of the apparatus, was proposed to carry out tests in laboratories. Effects of tie rods and boundary conditions of the CRE, including geogrid length, ground anchors at the end of the geogrids, and overburden, on the behavior of the CRE subjected to differential settlement and cyclic load were investigated.

In this study, four geogrids layers (G1-4) and three sand layers were used. The total thickness of the CRE was 30 cm. They were laid on a fixed plate simulating an abutment of a bridge and a moveable plate which simulated settlement of an embankment by jacking down it. Studying the effect of geogrid length, instead of increasing the length of a soil box, which is used for the CRE test, and the geogrid, an embedded geogrid was simulated by its pullout resistance. This resistance was applied at the boundary of the soil box with the dimensions of 1.2 x 0.4 x 0.8 m = length x width x height. As an embedded geogrid changed, the pullout resistance was changed corresponding to the embedded geogrid length outside the soil box. By using this physical model, a large-scale model test can be done in a laboratory where the space is often limited.

The effect of confining tie rods on behavior of the CRE subjected to differential settlement, and then cyclic load, with different confining tie rod spacing and preload in tie rods were studied. The confining tie rod spacing was 40 cm, 80 cm and no tie rod which simulates very large tie rod spacing. Preload in the tie rods of 0 and 3 kN was compared and analyzed. The results showed that surface settlement of the CRE decreased with a decrease in tie rod spacing and an increase in preload in tie rods. Large shear strain zone occurred between the tie rods with larger tie rod spacing.

Large width of shear zone caused more surface deformation. Reinforced soil became an integrated structure with close confining tie rods while the geogrids and soil seemed to be separated with large tie rod spacing. Tensile strain in the geogrids increased due to the cyclic loading. The increment of tensile strain in the lower layers was larger than those in the upper layers in cases with the close confining tie rods spacing.

The effect of geogrid length was investigated with different embedded geogrid length (resistance length) outside the soil box. The embedded geogrid lengths in a series of tests were 0, 0.29, 0.54, 0.81, 1.01, 1.26 and very long geogrid. When the embedded geogrid length is zero, the right end of the geogrid was laterally free. Infinitely long geogrid was simulated by laterally fixed condition at the right boundary of the soil box. It had large pullout resistance so that the geogrids were not pulled out. It was found that the surface settlement decreased with an increase in embedded geogrid length (increase in pullout resistance). It also showed that with a certain settlement, S_v, when geogrid length on an embankment, L_E, was greater than 18 times settlement, S_v, the slope surface changed slightly or remained unchanged, otherwise it changed significantly. This geogrid length consisted of the geogrid on the movable plate of the soil box and embedded geogrid (the embedded geogrids were out of the soil box). For example, with settlement, S_v, of 9.0 cm, when the length of geogrid on an embankment, $L \geq 18*9.0 = 162.0$ cm, the slope surface changes very small. In shear zone of the CRE, which was between the first and the second tie rods, on the moveable plate and near the fixed plate, shear strain in the case with short embedded geogrid (0, 0.29 m) was larger than that in long embedded geogrid (0.54, 1.26 m) case. In the shear zone, shear strain was concentrated. Tensile strain in the geogrids increased with an increase in embedded geogrid length. In the cases of short embedded geogrid, tensile strain at the bottom geogrids, near to a structure showed compression or small tension. This is because the CRE deformed like a mattress folded in a Z shape. However, in the cases of long embedded geogrid, all strain showed tension and the peak tensile strain shifts from the left to right with depth as the CRE behaved like a beam. Tensile strain increased under the cyclic loading and the increase of tensile strain in the lower geogrids (G3, 4) was larger than that in the upper geogrids (G1, 2). The force in tie rods decreased with the differential settlement in general, then decreased significantly with the cyclic loading.

Use of ground anchors at the end of the geogrids was considered to improve pullout resistance of the geogrids for better performance of the CRE. Ground anchors were used with three embedded geogrid length of 0.29, 0.54, and 0.81 m. When the anchors were used, surface settlements were smaller than those of the CRE without the ground anchors. However, the effect of anchors was negligible in the case with long embedded geogrids (0.81 m) due to the larger pullout resistance of the embedded geogrids. Tensile strain in the geogrids were larger in the cases with the ground anchors than in the cases without ground anchors. However, the increment in tensile strain due to the use of the anchors was small in the cases with long embedded geogrids. The force in the tie rods decreased in general.

Overburden was applied to the surface of the CRE to investigate the effect of pavement thickness on the settlement. It showed that the surface settlement increased with the overburden. Similarly, tensile strain in the geogrids also increased with the overburden. In the case with long embedded geogrid (0.81 m), the tensile strain increased linearly with the overburden. Furthermore, the tensile strain also increased linearly with the settlement.

論文の審査結果の要旨

地震などにより道路盛土が沈下し、橋台部との間に大きな段差が生じると、緊急車両の通行を阻害することから、その段差を軽減する段差抑制工法として、路床部に数層のジオグリッドを水平に敷設し、さらに鋼製タイロッドで鉛直方向に締め付ける、Confined Reinforced Earth (CRE: 拘束補強路床) 工法が提案されている。実大野外実験により大きな不同沈下に対しても実車両の通行性の確保が検証され、既に実現場への適用事例もある。しかしながら、補強のメカニズムやより効率的な補強法に関する研究はあまりなされていない。本論文は、拘束補強路床の変形と補強のメカニズムを調べ、さらにタイロッドの設置間隔と拘束力の影響、上載荷重の影響、ジオグリッド端面拘束条件の影響を、室内降下床模型実験と解析を通して検討を行っている。

本論文は、研究成果を８章に分けて記述している。

第１章では、ジオシンセティックスの機能と適用を概観し、橋台部と盛土間の段差抑制の必要性を述べ、本研究の目的と構成を述べている。

第２章では、補強土の補強メカニズム、ジオシンセティックスと土の相互作用、補強土構造の事例や補強土構造における拘束圧やジオグリッド長の影響などに関する既往の研究について述べている。

第３章では、模型実験について、使用材料の特性、模型地盤 (路床) の作製法、上載圧載荷法、ジオグリッドの引抜き試験と引抜き特性シミュレーターの開発、模型試験の降下床試験装置や試験手順、実験計画などを説明している。

第４章では、降下床実験やその後の繰返し載荷により拘束補強路床に生じる変形を計測し、タイロッドの回転や拘束補強路床に生じるせん断ひずみ分布を求め、拘束補強路床の変形メカニズムを検討している。その結果、降下床（沈下する盛土部に相当）上で固定部（橋台部に相当）に近いタイロッドで挟まれた領域でせん断ひずみは最も大きくなるが、それよりも外側の領域ではせん断ひずみはあまり増加しないことから、タイロッドの効果を示した。鋼製タイロッドの設置間隔が狭い程、またプレロードが大きい程、変形は抑制され、地表面の傾斜が軽減される。

第５章では、拘束補強路床の外側にジオグリッドを延長して拘束条件を変えることが不同沈下時の変形に及ぼす影響を検討している。室内模型実験では土槽を延長することは容易ではない。そこで、弾完全塑性的ジオグリッドの土中引抜き特性をバネとベロフラムシリンダーの空気圧で模擬する機構を独自に考案し、ジオグリッドの敷設長や埋設深さの影響を考慮した実験を実施した。ジオグリッドの敷設長が長い程、補強路床に生じるせん断ひずみは低減され、ジオグリッドに生じる伸びひずみは大きくなり、ひずみのピーク値の位置が固定端の上部から降下端の下部へと変化するという弾性梁と同様の挙動を示した。さらに繰返し載荷を行うと、伸びひずみは下部のジオグリッドほど増加する一方、タイロッドの張力は低下した。敷設長が長い程、車両の通行性とも関係する地盤表面最大傾斜は小さくなり、ジオグリッド敷設長が沈下量の約 18 倍以上あれば最大傾斜値はほぼ一定値に収束することから、今回の条件ではこれが適切な敷設長と考えられる。

第６章では、現場において十分な敷設長が取れない場合を想定し、ジオグリッド端部にアンカー板を設置したケースを、バネを追加しさらに最大引抜き抵抗を増加させることで模擬した。アンカーを設置すると、ジオグリッド敷設長が短い場合はジオグリッドの張力が増加し拘束補強路床の変形が抑えられたが、敷設長が長い場合には効果は相対的に小さかった。

第７章では、路盤などによる上載荷重が拘束補強路床の変形に及ぼす影響を調べている。１～ 2kPa 程度の小さな上載圧ではあまり影響は見られないが、4kPa となると沈下量が増加する。敷設長が長い場合はジ

オグリッドに生じるひずみは上載圧にほぼ比例して増加するが、敷設長が短い場合はそういう傾向は見られない。

第８章では、本研究により得られた結論を述べている。

本研究では、橋台部と道路盛土部の間で地震などにより段差が生じても緊急車両の通行を確保できる段差抑制工法として提案されている拘束補強路床工法について、既に実現場への適用事例もありながら、補強のメカニズムやより効率的な補強法に関する研究があまりなされていないことから、拘束補強路床の変形と補強のメカニズムを調べ、さらにタイロッドの設置間隔と拘束力の影響、上載荷重の影響、ジオグリッド端面拘束条件の影響を、室内降下床模型実験と解析を通して検討を行っている。さらに、模型実験においてジオグリッドの引抜き特性を簡易な機構で模擬できる装置を独自に考案するなど、研究の独創性、新規性、発展性が大きい。また、結論に至る種々の検討における厳密性も高く評価される。それらの点を総合的に判断して、博士の学位論文として合格と判定した。