THREE DIMENSIONAL CELLULAR CONFINEMENT SYSTEM CONTRIBUTION TO STRUCTURAL PAVEMENT REINFORCEMENT

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Synopsis: *The burgeoning demand for raw materials in road infrastructure development projects in India can be minimized by use of innovative techniques based on new developments in geosynthetics. New generation 3D cellular confinement systems (geocells) offer improved structural reinforcement for road construction that not only reduce pavement thickness while using inferior fill, but also increase the life-span of flexible pavements, particularly in soft soils. This technology can significantly reduce road repair, rehabilitation, maintenance, and most importantly the precious raw materials, thereby making the rapid infrastructure development more sustainable.*

Recent developments in geocell polymers, design theory and the reinforcement mechanisms that make geocells suitable for civil engineering standards have not been fully documented, although a number of laboratory, in-situ and academic research projects are underway. Results of studies to date demonstrate that the unique interaction of soil, cell and shape in cellular confinement systems act to stiffen the pavement foundations as a result of the soil confinement mechanism. This case study describes the in-situ testing, analysis and explanation of the structural contribution of a three dimensional cellular confinement system on soft soil. The adoption of such technology, particularly by developing countries, offers significant engineering, environmental and economic advantages.

1. INTRODUCTION

The enhanced performance and economies of geosynthetics to reinforce flexible pavements over weak subgrade is a key ingredient in the efforts to improve the Indian transportation infrastructure, faced by limited resources, problematic soils and the need for durable all-weather roads.

While the use of planar reinforcement, such as geotextiles and geogrids, in load support applications are widespread, the use of three dimensional cellular confinement systems (geocells) is limited due to uncertainties about its reinforcement capabilities as well as a lack of standardized design and testing methods. No doubt, the history of geocells initially developed for use with short term pavements has hindered its adaption by civil engineering professionals. However conventional geosynthetic material testing that does not reflect the composite structure of the cellular confinement systems, and the fact that in situ testing is complex and expensive, has also contributed to this situation. Testing the geocells for load support is a complicated procedure that can be divided into three independent phases:

- Measuring the stiffness and strength values of the geocell wall
- Measuring the ability of cell to withstand the radial stresses during service
- Measuring the composite (cellular section and granular material) to provide sufficient bearing capacity, rutting resistance and dynamic resilience

A major advantage of 3D cellular confinement systems is their ability to utilize fine grained granular materials that are unusable in 2D planar methods. For example, non-cohesive material such as sand attains sufficient strength and stiffness when confined in geocell encased soils (Rajagopal, Krishnaswamy, and Madhavi Latha 1999). The 3D vertical zone of influence enables the use of poorly graded and fine granular materials, including native soil, quarry sands, and recycled materials for heavy load support applications including heavy traffic pavements and railway substructures.

While the traditional HDPE based geocells tend to deform plastically over time, and can provide only short term confinement, new generation geocells from polymeric alloys can provide the long term stiffness and confinement necessary for traffic engineering standards. These cellular confinement systems are an example of an innovative road reinforcement technology that improves strength, reduces costs, and minimizes maintenance. The following case study documents an in-situ test of cellular confinement system demonstrating its utility in reinforcement for flexible pavement and describes the reinforcement mechanisms of the geocell system.

2. IN SITU GEOCELL REINFORCEMENT TEST

The Institute of Geotechnical Engineering and Mine Surveying at the Clausthal University of Technology in Germany conducted field tests on a 3D cellular confinement system supplied by PRS Mediterranean Ltd. (Annex 1). The goal was to examine the impact of the geocell reinforcement of the base layer of an asphalt surface course by installing subsurface measurement devices for long term monitoring. Phase I of the research aimed at determining the vertical stresses developed immediately underneath the reinforced granular layer and comparing them to those vertical stresses developed at the same elevated location in a control section. The Phase I field tests were carried out in August 2005 during the deep rehabilitation of Road K27 in the administrative district of Peine, Lower Saxony, Germany, which connects Federal Road B65 approx. 20 km west of Braunschweig, and Federal Road B1 35 km east of Hanover (Meyer, 2005).

The existing road pavement consists of an asphaltic concrete layer of approximately 200 mm on top of a 150 mm gravel base layer. The subgrade consists of sandy clay with an average low modulus E_{V2} = 23 [MPa] (CBR 4.6%). The two lane road has low drainage ditches on both sides and is closely located to each of the shoulders. According to Meyer (2005) the proximity of the drainage ditches to the road pavement provides insufficient lateral support, which combined with heavy traffic loads, results in cracking of the existing road surface and rutting along the wheel path. The existing pavement structure and gravel base course were rehabilitated several times in recent years.

2.1 Rehabilitation Methodology

Conventional rehabilitation of the existing road consisted of stabilizing the road shoulder foundation to improve the lateral support. In addition, new asphalt concrete layers were placed on the existing road surface. The rehabilitation process was as follows:

- Existing asphalt concrete layers: These were removed at a distance of 1-2 m from both sides of the road.
- Base layer: Gravel and soil under the removed asphalt layers were dug out to a depth of 700 mm (Figure 1).
- New gravel base layer: After compacting the subgrade, a new 700 mm thick gravel layer (32 mm max. particle size) was compacted in layers of 150 to 250 mm thickness with a vibrating plate compactor.
- Existing 1m wide strip in the middle of road: This was untouched and only existing cracks were filled.
- New asphalt layer: A total of 175 mm thick new asphalt concrete layer was applied over the whole width of the road on the renewed gravel layer (700 mm) and the middle strip of the asphalt road surface.

Figure 1: Subgrade (L) and installation of the new gravel base course 0/22 mm (R)

The alternative solution utilized the 3D Cellular Confinement System. The geocells were implemented instead of the 700 mm thick mineral gravel base course on a 500m section of the rehabilitated road as follows:

- Existing asphalt concrete layers: These were removed at a distance of 1-2m from both sides of the road.
- Base layer: Gravel and soil under the removed asphalt layers were dug out to a depth of 400 mm.
- New gravel base layer: After compacting the subgrade, a new 150 mm thick gravel layer was built and compacted (Figure 2).
- A nonwoven geotextile layer was installed on the compacted gravel layer.
- 3D Confinement System (single cell – 200 mm high x 210 mm long x 250 mm wide) was installed on the nonwoven geotextile (Figure 2).
- The geocell pockets were filled with gravel (22 mm max. particle size) until the old road surface height was reached, and then compacted (Figure 2).

Figure 2: Installation and Infill of the Geocell (L), Earth Pressure Cells (R)

After the installation of the 3D cellular confinement system, a new 175 mm asphalt course layer was applied. The asphalt course layer comprised a 100 mm thick base course 0/32 mm, a 40 mm thick binder layer 0/16 mm and a 35 mm thick wearing layer of SMA 0/8 mm. A comparison of the different rehabilitation sections is shown in Figure 3.

Geocell Reinforced Section | Middle Road Section | Conventional Unreinforced Section

Figure 3: Graphical representation of the different rehabilitated road sections

2.2 Installation of Earth Pressure Cells

In order to measure the underground stress induced by static plate measurements and from the traffic, 6 dynamic earth pressure cells were installed (Figures 2, 4). In the reinforced section one earth pressure cell was located directly under the geocell layer.

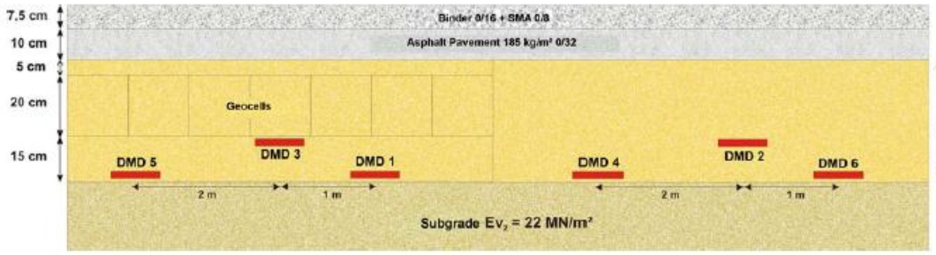

Figure 4: Typical section of reinforced vs. conventional pavement and location of pressure cells

2.3 Measurements of Vertical Stress in Base Soil

As shown in Figure 5 below, measurements of the vertical stress were taken at three points in identical positions in each of the pavement types. The static measurements were taken by incremental loading of a 300 mm diameter plate on the surface of the granular layers according to the German test procedure – *Plattendruck versuch nach DIN 18134*. The graphical representation of the loading, as recorded by pressure cells DM2 (unreinforced) and DM3 (reinforced) are shown in the following illustration.

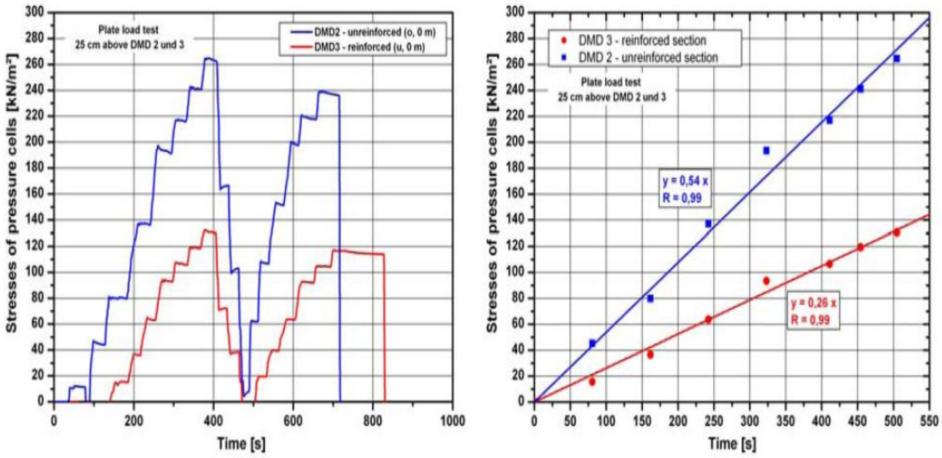

Figure 5: Graph of loading results as recorded by pressure cells DM2-DM3

As can be seen from the above results, there is a 50% reduction in the vertical stress as recorded by pressure cells DM2 and DM3. The operational significance of the static load measurements is that the geocells with granular infill create a semi-rigid mattress in which the stress is distributed over a wider area, thereby decreasing strain on the base layers below.

3. BACK-CALCULATION OF STRUCTURAL VALUE OF GEOCELL LAYER

As a result of the interaction of the three dimensional geocell structures with granular infill, a reinforced soil layer is created with improved properties in comparison to the conventional unreinforced method. Quantification of the structural improvement can be performed with the aid of Elastic Stress Analysis. The elastic parameters of the pavement layers are taken from the Israel Public Works Guidelines June 2003. The values are shown in the following table:

Table 1: Elasticity Parameters of the Pavement Layers in the Geocell Test

	Elasticity Parameters	**Notes**
Asphalt	E_{ac} $[MPa] = 3000$ $\upsilon_{ac} = 0.35$	The dynamic modulus is measured at a temperature of 25^0 C, frequency of 10 Hz, single axis test
Base	$E_b = E_{ab}$ x $(1+0.0067$ x $h_b)$ $\upsilon_b = 0.35$	E_b $[MPa] \leq 700$; h_h in mm
Sub-base	$E_{sb} = E_{sg}$ x $(1+0.003$ x $h_{sb})$ $\upsilon_{sb} = 0.35$	E_{sb} $[MPa] \leq 300$; h_{sb} in mm
Subgrade	E_{sg} $[MPa] = 14$ x CBR [%] $\upsilon_{sg} = 0.40$	2 < CBR [%] < 12

Elastic modulus of the base layer:

$$E_{sg} = 14 \cdot CBR[\%] = 14 \cdot 4.6 = 64.4[MPa]$$

Elastic modulus of the granular layer with thickness of 150 mm:

$$E_{sb} = E_{sg} \cdot (1 + 0.003 \cdot h_{sb}[mm]) = 64.4 \cdot (1 + 0.003 \cdot 150) = 93.4[MPa]$$

In order to calculate the elastic modulus of the upper aggregate layer at a thickness of 250 mm, the re-calculation is performed according to a trial and error methodology as described in Figure 6 below.

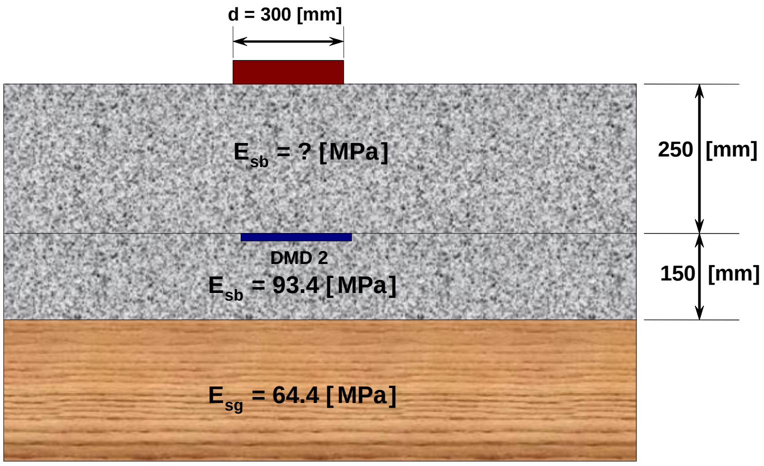

Figure 6: Description of aggregate layer and pavement modulus above pressure cell DM2

- Vertical circular plate pressure on surface of granular layer was 411 [kPa].
- Vertical stress (σ_y) measured in unreinforced DMD 2 pressure cell was 217 [kPa].
- Vertical stress (σ_y) measured in reinforced DMD 3 pressure cell was 107 [kPa].

A total reduction of 51% in the vertical stress (σ_y) was measured underneath the reinforced granular layer. A finite element analysis program (Geo-Studio Sigma/W) was used to analyze the results of the two sections. The analysis showed that the Elastic Modulus of the unreinforced granular layer (250 mm in height) was E_{sb} = 100,000 [kPa]. The pressure bulbs of vertical stress (σ_y) are shown in Figure 7 and Figure 8.

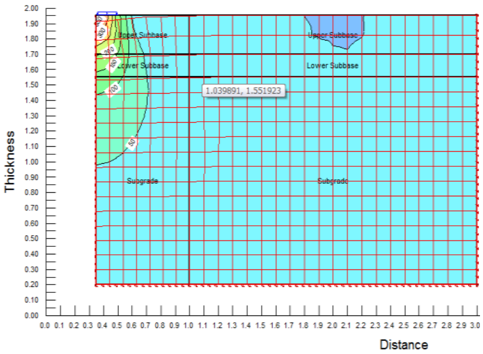

Figure 7: The evaluated vertical stress (σ_y) distribution in unreinforced section.

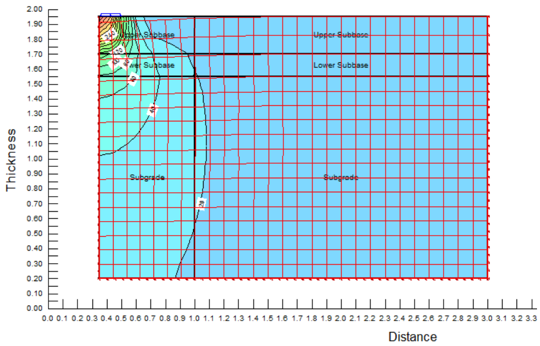

Figure 8: The evaluated vertical stress (σ_y) distribution in the reinforced section.

As can be seen in Figure 7 the vertical stress (σ_y) underneath the unreinforced granular layer is identical to the measured stress in the field test. In order to find the Elastic Modulus of the reinforced granular layer (25 cm in height) the modulus was changed until the vertical stress (σ_y) underneath the reinforced granular layer was close enough to the measured stress in the field test. It was found that the Elastic Modulus of the reinforced granular layer (25 cm in height) was E_{sb} = 500,000 [kPa]. The vertical stress (σ_y) distribution is described in Figure 8. Therefore, it can be concluded from the measured vertical stress underneath the upper granular layer that the three dimensional confinement system improves the pavement's structural soundness by a factor of five:

$$\frac{E_{reinforced}}{E_{unreinforced}} = 5$$

3.1 Stress Measurement on the Asphalt Course

After completing the rehabilitation of the gravel base course and the new asphalt pavement a vehicle crossing test was performed with a heavy truck (5 axles and approximately 41 tons) crossed the road at different speeds. During the vehicle crossing tests, the stresses in the underground were measured by the installed earth pressure cells at a depth of 425 and 575 mm. The stresses measured by the earth pressure cells at a depth of 425 mm (DMD 2 - unreinforced; DMD - reinforced) are shown in Figure 9.

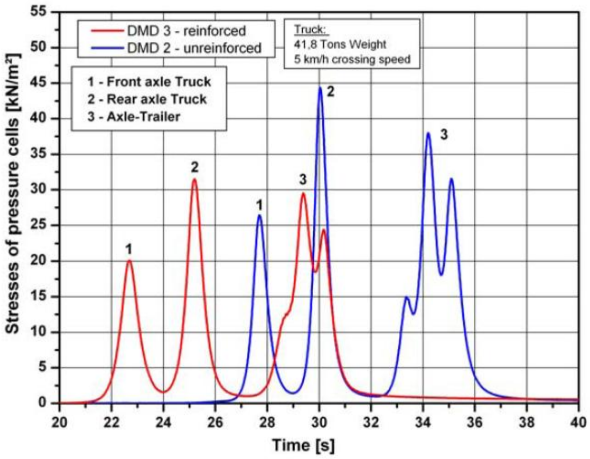

Figure 9: Vertical stresses caused by a heavy truck moving at 5 km/h

The results show the individual passage of all three truck axes in the reinforced and unreinforced section. The stresses measured during the truck passages are about 23-28% lower in the reinforced section independent of the respective axis. Tendentious similar results can be observed at passage of the truck at a speed of 40 km/h.

4. CELLULAR CONFINEMENT SYSTEM REINFORCEMENT MECHANISM

4.1 Overview

The Cellular soil confinement, stabilization and reinforcement systems are comprised of three-dimensional, interconnected cells that form a honeycomb structure, also known as geocells. The cell walls are typically textured and patterned with protuberances that enhance friction. When filled with granular material, a new composite structure is created from the interaction of the geocell and the confined soil. This composite cellular confinement system vastly enhances the physical and mechanical properties of granular materials enabling their use in load bearing (Koerner, 2005).

Figure 10: Cellular Confinement System

A new generation of geocell technology utilizes a unique polymeric alloy, which combines the fatigue resistance and low temperature flexibility of HDPE with the dimensional stability and creep resistance of engineering thermoplastics. This alloy is non-degradable, resistant to chemicals, and humidity, and it retains its dimensional stability properties under thermal cycling. The geocell sheets are fabricated by extruding and welding strips into honeycombed sections under certified quality control manufacturing processes.

The following paragraphs (Figures 11-16) illustrate the various resistance, frictional and hoop stress forces that act on an advanced composite cellular confinement system as a result of the specific geotechnical interaction of the geocell material, soil and geometry (Tsorani, 2008).

4.2 Unreinforced Soil Bearing Capacity

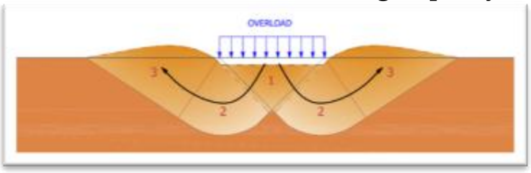

Figure 11: Shear punching

The following figure illustrates the effect of loading on unreinforced soil. The soft subgrade is punched and sheared under relatively low load resulting in a bearing capacity failure.

4.3 Reinforced Soil Bearing Capacity

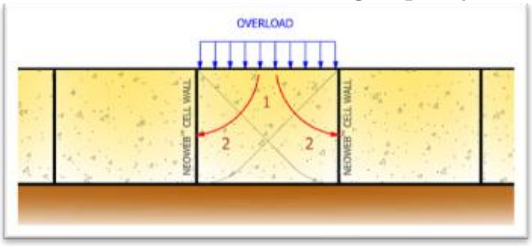

Figure 12: Confinement decreases punching and increases bearing capacity

In the cellular confinement system, vertical loading on the confined infill in the geocell results in high lateral stress and resistance on the stiff cell walls. The result is a decrease in punching, increase in bearing capacity and smaller peak settlement.

4.4 Lateral Stress on Cell

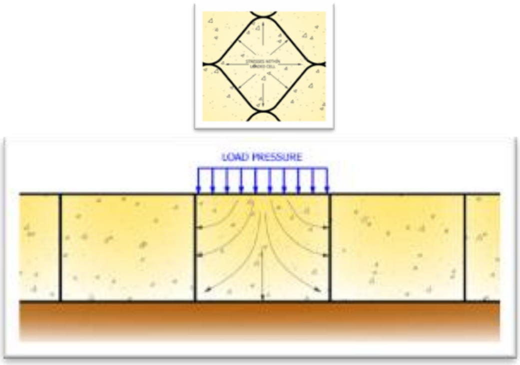

Figure 13: Stresses within the cell

When the soil confined within the cell is subjected to pressure, it causes lateral stresses on the perimeter cell walls**.** These stresses increase the shear strength of the confined soil, thus creating a stiff mattress, which distributes the load over a wide area.

4.5 Hoop Stress Development

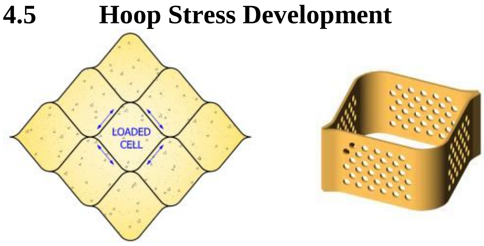

Figure 14: Three dimensional hoop stress

The three-dimensional structure confines the infill soil, limiting lateral deformation. Lateral expansion of the infill is restricted by high hoop strength.

4.6 Passive Resistance of Neighboring Cells

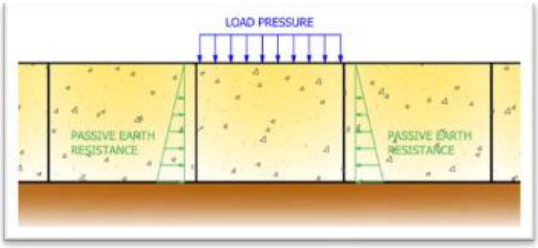

Figure 15: Passive earth resistance

In addition to the confinement by the stiff cell walls, soil contained in adjacent cells provides additional resistance against the loaded cell through passive resistance.

4.7 Cell Walls Interface Friction Resistance

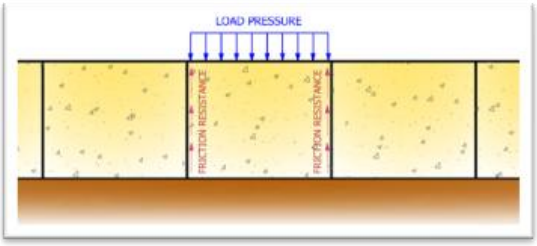

Figure 16: Interface Friction Resistance

The horizontal stresses applied on walls of the loaded cell increase the interface friction resistance between soil infill and the perforated and textured cell walls. The increased vertical frictional resistance diminishes stress reaching the subgrade.

5. CONCLUSION

In situ field testing of the cellular confinement system demonstrated that it reduced vertical stress of the reinforced granular layer by more than 50% on low bearing capacity subgrades. Finite element analysis of the test results revealed that the bearing capacity of the subgrade layer increased by approximately 2.5 times.

The reinforcement mechanism of the unique polymeric alloy composition and geometric shape distributes loads over a wide area, creating a 3D geocell mattress with high flexural strength and stiffness. This mattress decreases vertical differential settlement, improves shear strength, and enhances load-bearing capacity.

The results of the test show and the description explains how the use of geocells for reinforcement enables a reduction in the thickness of structural support elements – both the substrata and asphalt course – while at the same time improving the performance of non-cohesive and inferior fill, such as fine granular soils and recycled material.

Not only does this decrease the amount of excavation, haul and infill activities, with their associated economic and environmental gains, but reinforcement with geocells also extends the road service life of pavement structures, thereby lowering the operational costs and maintenance requirements. This enables transportation management professionals to shift more of their limited resources to the construction of new roads as opposed to repair, maintenance and rehabilitation.

Suitable for new road construction, as well as for the rehabilitation of distressed roads, cellular confinement systems can be used in a range of flexible pavement types from high-traffic paved highways to low volume unpaved roads. This has particular relevance to countries like India that seek to provide durable all-weather roads for access and development in remote rural regions.

As an inherently sustainable construction method, the geocell composite systems utilize less raw materials during construction than conventional techniques, while enhanced service life of new geocell technology significantly reduces long term road maintenance. The bottom line is that advanced cellular confinement systems provide a wealth of environmental, social and economic benefits in any country's efforts to improve road transportation infrastructure.

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