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Arch Structure Concept in Lightweight Fill Design

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Abstract: Construction of road embankment over soft soils can cause significant non uniform excessive settlements that contribute to uneven road surfaces. This is due to the properties of soft soil which have low shear strength, high water content and high compressibility. These properties of soil are quite difficult and challenging to work with. This research is focused on how to mitigate the non-uniform settlement of embankments on soft soil using an innovative arch structure concept design incorporating with the current construction method of expanded polystyrene (EPS) as lightweight fill material. EPS are lightweight fill materials which are low density, stable, inert, environmentally safe fill rigid mats for road construction. However, they are large bulky blocks and have high buoyancy characteristics which will be unstable when high water table arises. The arch structure design reduces the use of EPS block while achieving almost the same performance as the conventional design. Physical modelling is used in this research to analyse the performance of this conceptual arch structure using a test box, sandy soil as embankment and wooden blocks as EPS. The concept of arch structure is implemented by removing some of the blocks at the base and setting up three different layout arrangement of spacing and thickness of the blocks which are called mixed staggering (a), mixed staggering (b) and lateral staggering. The performance of the design was measured by analyzing the settlement of the three arrangement layouts. The settlement observed was monitored photographically and measured with markings labelled on the test box. It was found that the layouts of mixed staggering (b) have is proven to reduce the excessive non-uniform settlements compared to the lateral staggering and mixed staggering (a). Hence, this research has established a suitable design guide using a mixed staggering arch structure fill material which is light and strong to withstand heavy loading to reduce ground settlement.

Keywords: Soft soil, settlement, lightweight material, arch structure

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1. Introduction

Malaysia has had many road construction failures due to the engineering problems associated with soft soil characters such as high compressibility, low shear strength and low permeability [1]-[3]. Therefore, many technologies have been developed to overcome these problems. There are various types of fill materials adopted in road construction over the last 50 years; materials such as sawdust and bark residue from timber industry, geotextile, foamed concrete materials and LWA (Light Weight Clay Aggregate). One of the most used current technologies in road construction project is expanded polystyrene (EPS) as shown in Fig. 1 [4].

EPS geofoam can be used to replace marine clay or in place of heavy fill materials to prevent sudden settlement on the underlying soils and adjacent structures [5]. EPS are lightweight foam plastics, which is manufactured into blocks, and commonly used as a structural backfill. It has a unit density that can be roughly as low as one pound per square foot, nearly 100 times lighter than most soils [6]. The primary application of EPS is to reduce the self-weight of embankment soil constructed on top of soft soils as shown in Fig. 2.

EPS are big bulky lightweight materials that will face problems when there is a rise in water table. This is due to its low density and high buoyancy [6] where the water can displace its arrangement and produce voids in the ground. Due to this, the blocks arrangement may be uneven and the unexpected occurrence of the voids between the block may result to road failure.

Fig. 1 – Expanded polystyrene (EPS) as a filling material in road construction [7]

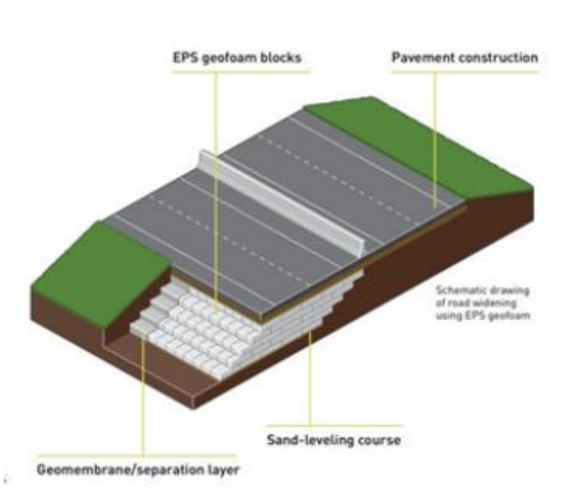


Fig. 2 – Road Embankment Construction using EPS Geofoam

This study proposes a design approach of an arch structure concept within lightweight fill technology. Arch is one of the oldest structural elements used in architecture and engineering construction for centuries. In the Romans times, many structures such as bridges, aqueducts and drainage systems were built using masonry arch concept and constructed from natural stones or bricks [8]. Therefore, the masonry arch is the most efficient structural element to span openings [9]. The semicircular arches as shown in Fig. 3 are the most often used especially in bridge construction due to its structural efficiency.

This concept of an arch structure for the design of fill material using EPS blocks will provide various benefits such as providing extra support and will also reduce the self-weight of the embankment soil. The area under the arch provides a void that will not fail due to its structural integrity. Hence this will provide less usage of EPS blocks while achieving almost the same performance as the conventional design. Also in this research, different arrangement of the blocks was studied to determine the best construction design that provides the least settlement.

Fig. 3 – Typical arch structure used for bridges.

2. Experimental Design

This research is focused on a new design model of lightweight fill material in the concept of arch structure. The fill material that will be used in the study will comprise of length (L), depth (D) and breath (B) of 7cm x 2.3 cm x 1.5cm respectively of the wooden blocks. The test also includes the analysis of the orientation and the arrangement of the fill material blocks for the structural design of the conceptual physical model.

A test box was prepared to hold the model embankment with the blocks as shown in Fig. 4. The box is rectangular in shape with 43 cm in length, 5 cm in width and 10.5 cm in height. The opening at the bottom of the box is for the blocks to be pulled out to create an arch structure. The blocks is arranged to three different arrangement layouts which are lateral staggering, mixed staggering (a), and mixed staggering (b). The blocks are arranged according to these layouts before the sand was put into the box. The sand used for the modelled embankment passes sieve 0.063 mm and it was compacted with a flat and heavy load to prepare the embankment with same density, mass and height for each different arrangement.

Fig. 4 – Test box for physical modelling

In preparation of the physical model, the arrangement of the spacing of the blocks (S) is considered an important element that contributes to the failure pattern due to its structural stability. The spacing of the blocks will be measured from the left edge of the arrangement. Each type of arrangements of lateral staggering (Fig. 5), mixed staggering(a) (Fig. 6) and mixed staggering (b) (Fig. 7) will be tested with different block spacing of (S) = 0, 0.1, 0.2, 0.3, 0.4, 0.5 cm.

The arch structure will be created for each layout of arrangement and different spacing (S) respectively by removing the blocks at the bottom of the box. Then, the settlement is recorded by photographic analysis. The box is labelled with a horizontal line at every 15 cm. This creates a settlement indicator for the embankment so that settlement can be recorded at 7 different levels as shown in Fig. 8.

A black powdered indicator was also placed for each level in the sand embankment to measure the settlement. Hence, any movement in the soil or the settlement then can be measured from the levels that had been marked on the box. The highest settlement was recorded for each level at any point to analyse the settlement behaviour.

It should also be noted that measurements should be taken carefully while measuring the settlement. Readings should be taken where the eyes of observant must be perpendicular to the level of indicators.

The results for each experiment will be compared through the graphical analysis where it is used to find the most suitable design in terms of spacing of the blocks to design an arch structure filler material.

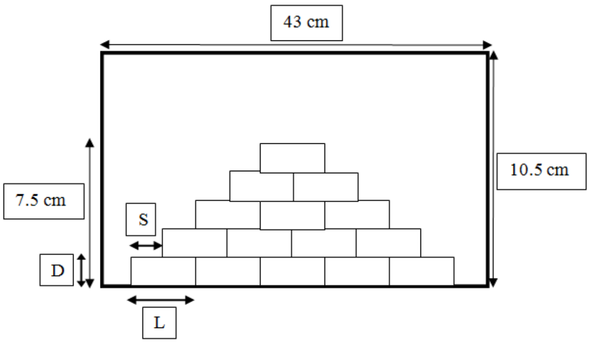


Fig. 5 – Arrangement layout Lateral Staggering

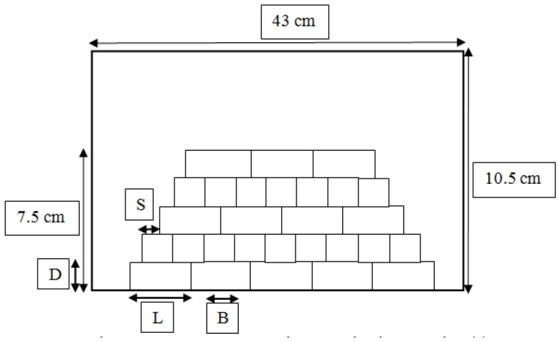


Fig. 6 – Arrangement layout Mixed Staggering (a)

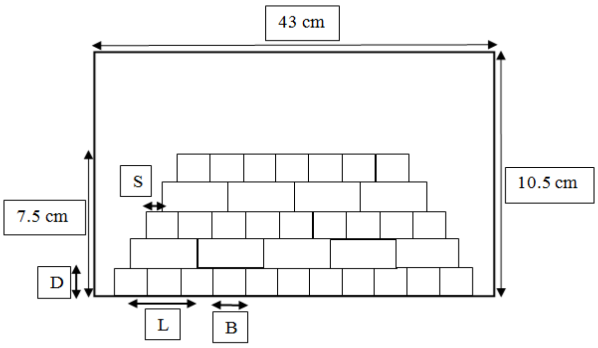


Fig. 7 – Arrangement layout of Mixed Staggering (b)

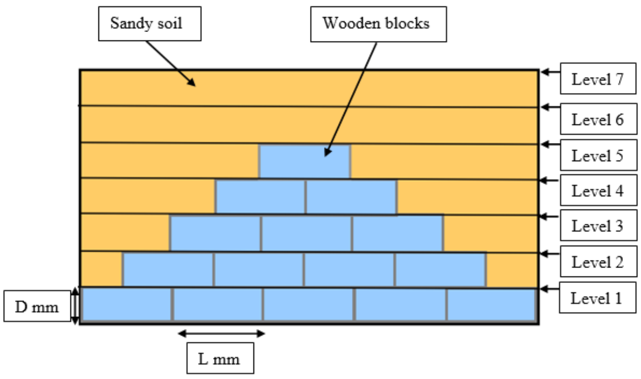


Fig. 8 – Illustration of the front view of embankment model

3. Results and Discussion

The analysis was done by photographic analysis where the picture of the model was taken before and after some of the blocks were pulled out from under the model. The settlement can be seen after the blocks were pulled out from the bottom of the model to create an arch structure. The experiment is repeated for each spacing (S) as describe in the previous section.

Fig. 9 shows the actual image of the lateral staggering layout model for spacing (S) of S = 0 cm to S = 0.5 cm after some of the blocks were pulled out from the bottom. It can be seen that settlement occurs excessively for spacing (S) of 0 cm and 0.1 cm. Hence this arrangement of blocks is not suitable to be used for an arch structure design. It is also observed that the settlement tends to decrease as the spacing (S) becomes larger.

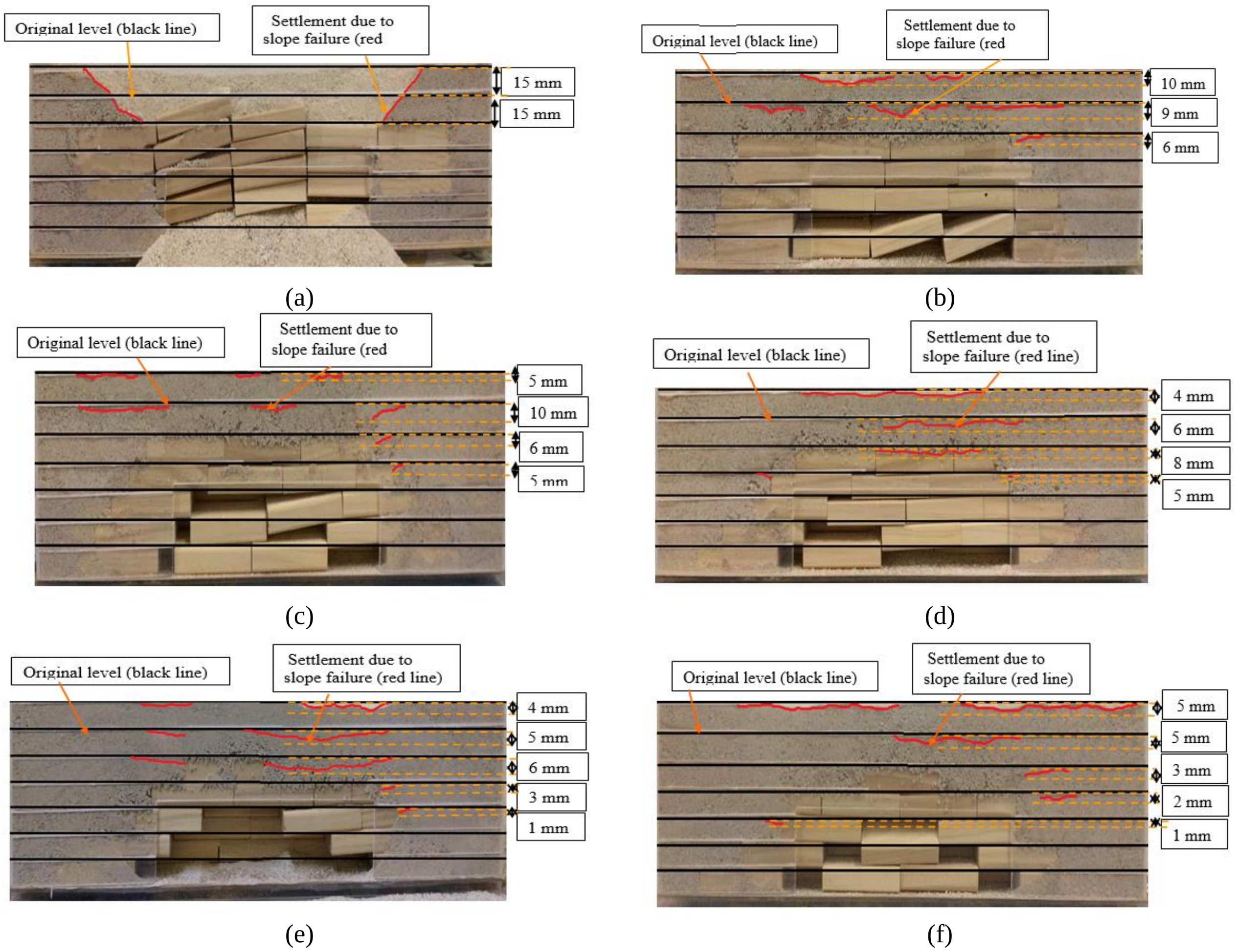
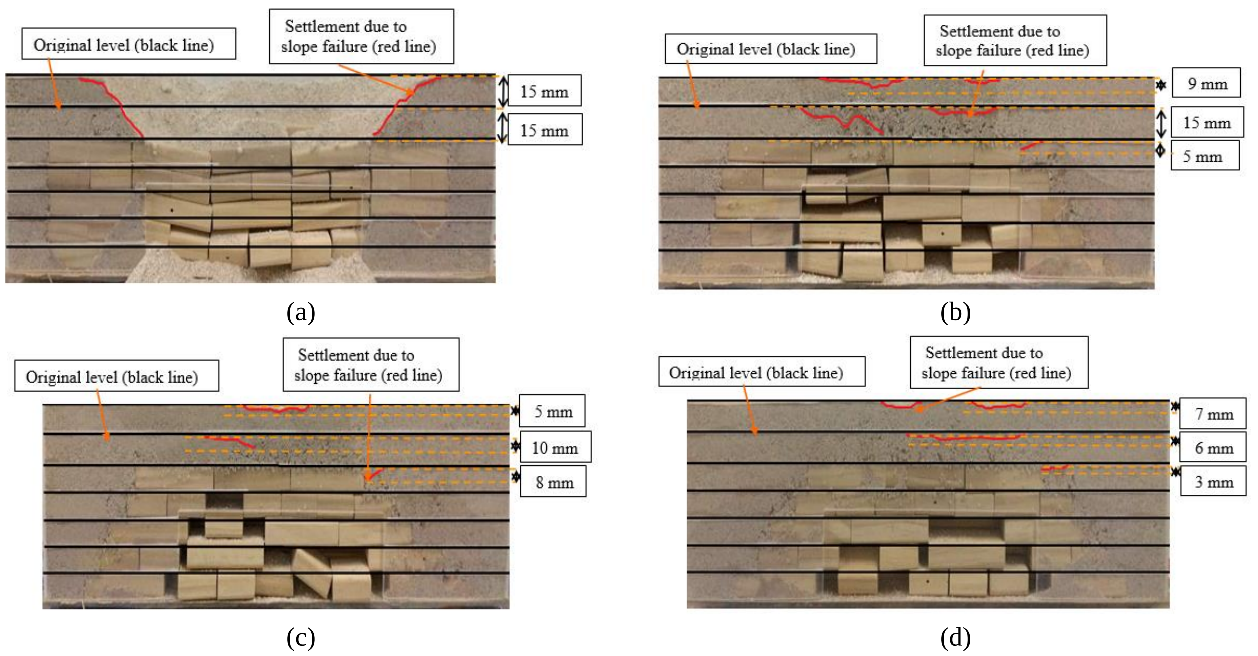
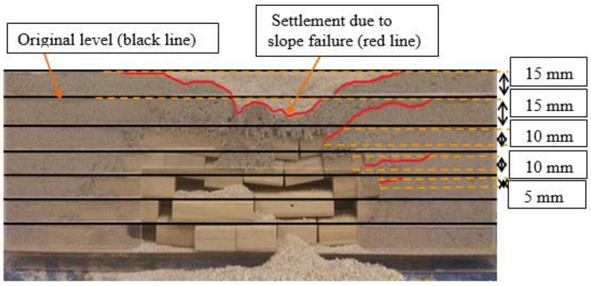


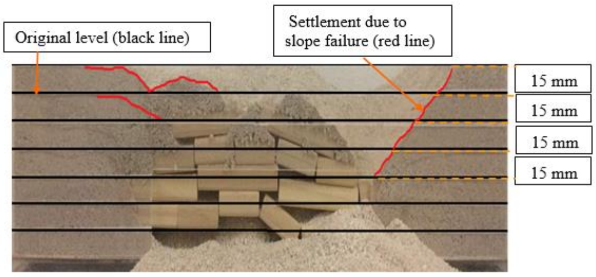
Fig. 9 – Settlement observation for the formation of an arch structure for lateral staggering layout with spacing (S) (a) S = 0cm, (b) S = 0.1cm, (c) S = 0.2cm, (d) S = 0.3cm, (e) S = 0.4cm and (f) S = 0.5cm

Fig. 10 shows the behaviour of the settlement for the formation of the arch concept for the mixed staggering (a) layout of spacing, S = 0 to S = 0.5. Overall observations indicate that this type of arrangement layout showed more settlement occurred as compared to the lateral staggering layout.





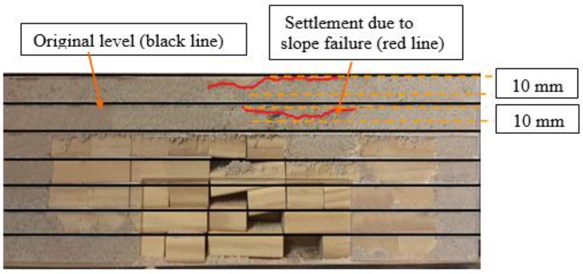
(e)



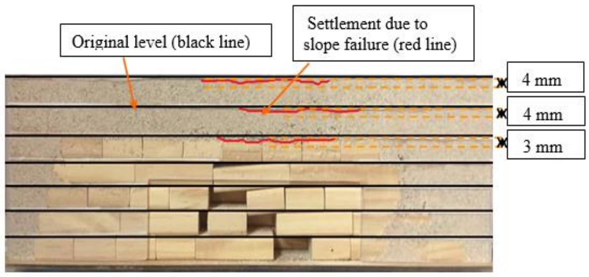
(f)

Fig. 10 – Settlement observation for the formation of an arch structure for the mixed staggering(a) layout with spacing (S) (a) S = 0cm, (b) S = 0.1cm, (c) S = 0.2cm, (d) S = 0.3cm, (e) S = 0.4cm and (f) S = 0.5cm

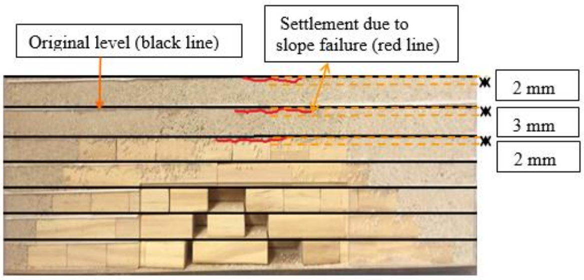
Lastly, the observations for the mixed staggering(b) layout is shown in Fig. 11. The figures showed all settlements after the arch design was prepared with different blocks spacing (S) of S = 0 to S = 0.1.



(a)



(b)



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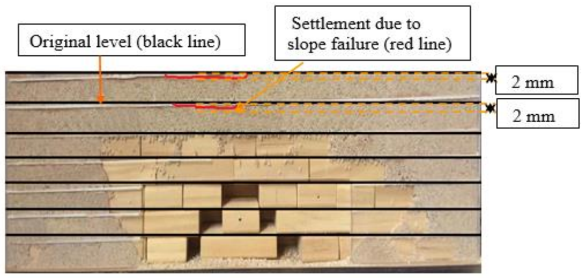

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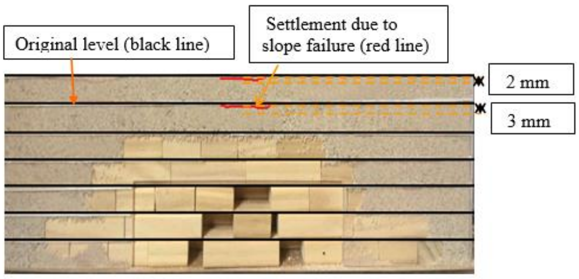
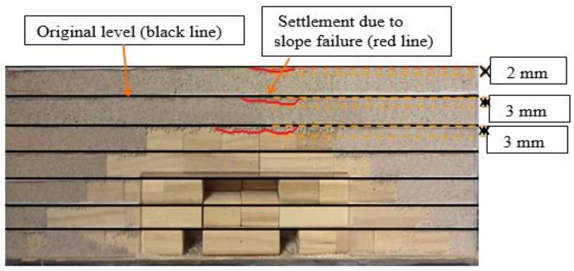


(e)



(f)

Fig. 11 – Settlement observation for the formation of an arch structure for the mixed staggering(b) layout with spacing (S) for (a) S = 0cm, (b) S = 0.1cm, (c) S = 0.2cm, (d) S = 0.3cm, (e) S = 0.4cm and (f) S = 0.5cm

With the photographic analysis done for all the arrangement and spacing (S) for the model, a graphical representation is then plotted to show the settlement behaviour for all the models.

Based on the data collected, the data have been analysed and is presented in the following graphical analysis of settlement versus the depth of the embankment. The depth of the embankment is presented by the levels that were mark on the test box of the model. The decrease in level means an increase in depth of the embankment. Fig. 13 shows the settlement for all the arrangements of lateral staggering, mixed staggering(a) and mixed staggering(b) at a spacing of S = 0. From the graph, it shows that the layout of lateral staggering and mixed staggering(a) have the same highest reading of settlement, which is 15 mm at level 6 and at level 7. While the layout of mixed staggering(b) shows its maximum reading of 10 mm at level 6 and at level 7 which is the lowest among the three layouts.

Fig. 14 to 18 then shows the settlement analysis for all the layouts from spacing (S) = 0.1 to (S) = 0.5 respectively. From all of the observations of the analysis of the graphs, it is seen in Fig. 18 that the settlement from the layout of mixed staggering(b) with a 0.5 spacing (S) gives the lowest settlement reading among all the spacing from different layouts. Hence, this will be the most suitable design that can be used to from an arch structure concept of lightweight fill material construction for mitigating uneven settlement.

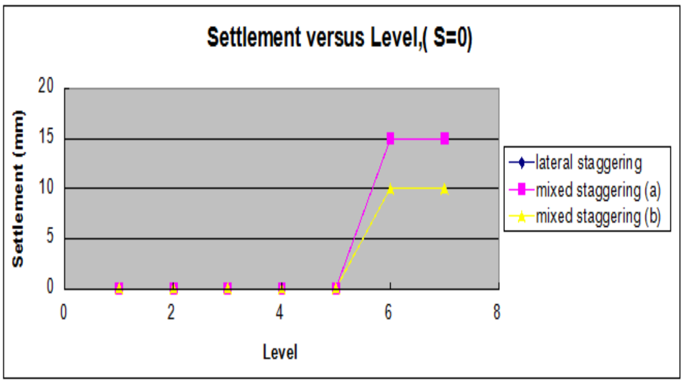


Fig. 13 – Graph of settlement reading with S=0cm between lateral staggering, mixed staggering (a) and mixed staggering (b)

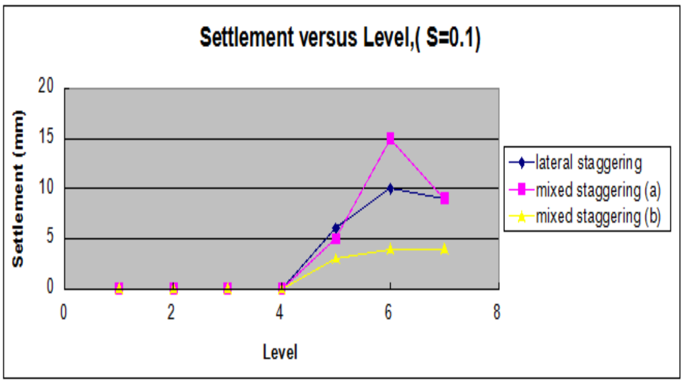


Fig. 14 – Graph of settlement reading with S=0.1cm between lateral staggering, mixed staggering (a) and mixed staggering (b)

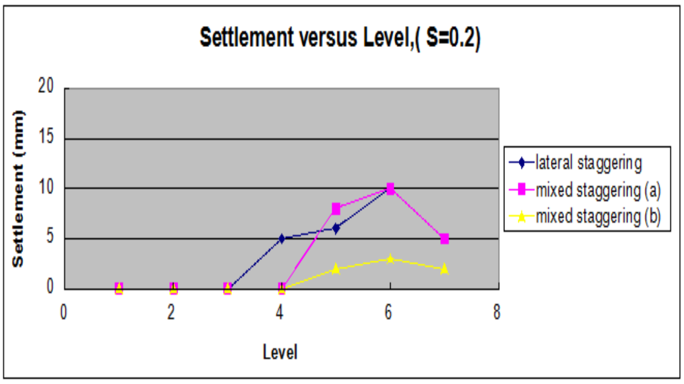


Fig. 15 – Graph of settlement reading with S=0.2cm between lateral staggering, mixed staggering (a) and mixed staggering (b)

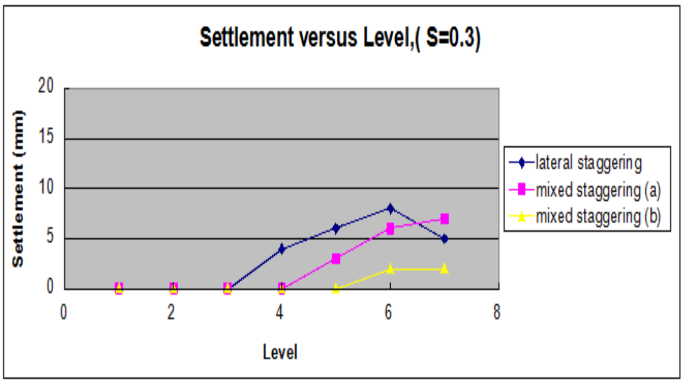


Fig. 16 – Graph of settlement reading with S=0.3cm between lateral staggering, mixed staggering (a) and mixed staggering (b)

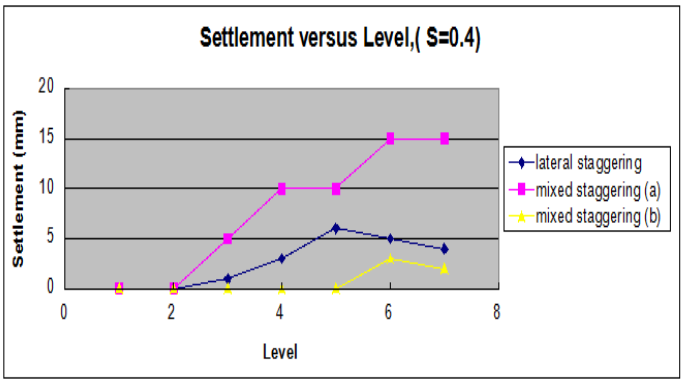


Fig. 17 – Graph of settlement reading with S=0.4cm between lateral staggering, mixed staggering (a) and mixed staggering (b)

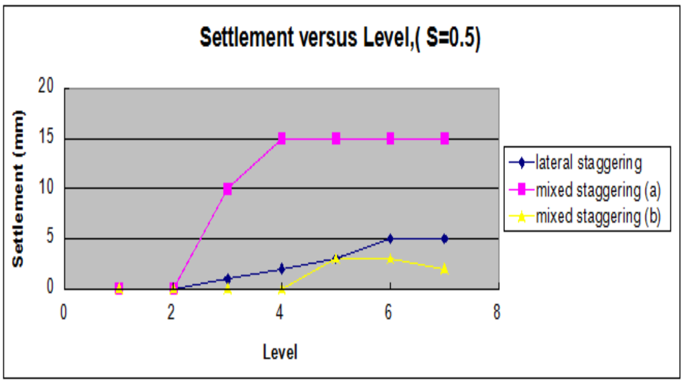


Fig. 18 – Graph of settlement reading with S=0.5cm between lateral staggering, mixed staggering (a) and mixed staggering (b)

4. Summary

This research has come to propose a new design guideline or procedure in the construction of innovative lightweight fill material as well as an appropriate construction standard. The arrangement of an innovative lightweight fill material for an arch structure was studied with the consideration of implementing different spacing (S) of the blocks.

The suitable design of fill material as an innovative lightweight incorporating with an arch structure has high potential to be used as road embankment fill that can withstand heavy loading. The behaviour of fill block which are lightweight and have suitable arrangement can reduce the excessive non-uniform settlement and the overall weight of the structure used as a foundation of structure on soft soil.

This research has found that the layout of mixed staggering(b) with a spacing (S) of 0.5 cm is the most suitable design of fill material that can be optimized to be used for an arch structure to mitigate excessively non-uniform settlement.

The best arrangement of innovative lightweight fill material can avoid from the phenomenon of sinkhole. Sinkhole is formed from the effect of depression in the ground that caused by collapse of the surface layer. So, this research proposed the most suitable design to avoid from sinkhole incorporating optimized arch structure concept.

Other than that, the suitable design of fill material as an innovative lightweight has high potential to be used as road embankment fill that can withstand heavy loading. The behaviors of fill block which are lightweight and good in arrangement can reduce the excessive non-uniform settlement and the overall weight of the structure and used as a foundation of structure on soft soil.

Last but not least, to make a better conclusion from the performance of fill blocks, it can be recommended that the same fill material to be evaluated together with other form of lightweight material when subjected to arch structure concept.

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