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Filtration Behaviour of Cohesionless Soils under Dynamic Loading Condition

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Summary: The filtration behaviour of 'capping' material, also known as filter soil, used in railway track was investigated under dynamic loading conditions. A filtration apparatus was designed and commissioned at Monash University to undertake filtration tests under dynamic train loading. Limited laboratory tests were carried out on various base-filter soil combinations and different D_{15}/d_{85} ratio under both static and dynamic loading conditions. Test results indicate that a D_{15}/d_{85} ratio of 10 under dynamic loading may be considered as unconservative. Similarly, the upper bound value of 10 is observed to be high for broadly graded cohesionless soils thus leading to 'failure' under dynamic condition.

INTRODUCTION

The sub-ballast layer, also known as capping layer, placed between the ballast and subgrade of a railway track provides an effective filter interface by preventing migration of fines from the subgrade into the top ballast layer or vice versa. Under dynamic loading, this sub-ballast also allows water to drain into the top ballast layer and, hence, minimize excessive pore water pressure development in a saturated subgrade. Inadequate design of sub-ballast material over wet formation could lead to a fouled track condition associated with speed restriction and increased track maintenance costs.

The design of a sub-ballast layer in railway track is generally performed using the conventional filter design criteria based on the static loading condition. However, a dynamic behaviour resulting from train loading is observed at the sub-ballast-subgrade interface of a rail track. Therefore, adopting existing filter design criteria often leads to migration of fines from the subgarde to the top ballast layer, which can lead to severe track pumping.

A laboratory filtration test apparatus was built at Monash University to simulate the filtration behaviour observed at the sub-ballast-subgrade interface under dynamic loading. This test apparatus can also be used to study the filtration process in other applications such as road pavements and drainage systems in geotechnical designs. Laboratory tests were carried out on cohesionless sub-ballast-subgrade soils under dynamic loading conditions. In this paper, the effect of the dynamic component of train loading on filtration behaviour of cohesionless soils will be discussed with respect to the D_{15}/d_{85} ratio and the uniformity coefficient (C,). The mechanism of self-filtration under dynamic loading will be also addressed.

FILTER DESIGN CRITERIA

The filter design criteria were first introduced by Terzaghi (1922) and were based on the grain size distribution of the protected soil and the filter material. In selecting a filter material, Terzaghi proposed the following requirements:

(a) The 15th percentile particle size of the filter material should not be more than four times as large as the 85th percentile particle size of the base soil (protected soil). This is usually known as 'piping requirement' e.g. $(D_{15}/d_{85}) < 4$, where D=particle size of filter soil and d=size of base soil. This criterion is related to the stability of the filter from piping. It is commonly interpreted that the 15% of the coarsest size of the base soil, when prevented from entering into the filter, will form a filter on its own (self-healing effect) by retaining the remaining ***85%*** of the base soil.

(b) The 15th percentile particle size of the filter material should be at least four times as large as the 15th percentile particle size of the base material. This is known as the 'permeability requirement', e.g. (D_{15}/d_{15}) > 4. This criterion is related to the permeability requirement of the filter material.

Several researchers carried out laboratory investigations to determine the value of D_{15}/d_{15} (Bertram, 1940; Lund, 1949; U.S.C.E., 1941, 1953; Soares, 1980; Sherard, 1984; Honjo, 1985; Lafleur et al., 1989, Kwang, 1990; Haque, 1992; Indraratna et al., 1996). The suggested value for D_{15}/d_{85} found ranged from 4 to 10. A value of 4 for piping ratio was observed to be more conservative for widely graded soil, such as the capping material used at the interface of ballast and subgrade soil in a railway track.

LABORATORY INVESTIGATION

Filtration Apparatus

The test apparatus consists of a Perspex cylinder 125mm in diameter and 200mm in height. The inlet and outlet valves are connected at the top and base of the cylinder, respectively. The inlet valve is connected to an air/water reservoir which connects with the dynamic pressure controller. The dynamic pressure controller can apply both static and dynamic pressure simultaneously by adjusting the appropriate pressure control knobs. This pressure controller could be used to apply a maximum dynamic or static pressure of 150kPa with a frequency of 0.06 to 1Hz. Although, the pressure controller has a very low frequency range compared to a 1 to 40Hz frequency normally used in a railway track modeling, it could be used to study the impact of dynamic train loading on the filtration process. In this study a frequency of 0.16Hz was used for all the tests.

Specimen Preparation

The base and filter materials were placed in three layers within the testing cylinder. The filter and base soils were mixed with 5% and 15% of water respectively to avoid segregation during placement and to achieve good compaction (Haque, 1992). At first, the filter material was placed within the cylinder in three layers with each layer being compacted using 50 blows of a metallic tamper. A tamper of 30mm in diameter and 260gm of weight with an approximate height of fall of 50mm was used in this investigation. The base soil was placed within the cylinder into layers and compacted using the tamper. Filter and base soil thicknesses of 50mm and 70mm were used in this study. A minimum base soil thickness of 50mm was suggested by Lund (1949). In all the tests, the samples were compacted to 90 to 100% of relative density.

After the sample was leveled at the top surface inside the cylinder, a layer of lead shot was placed on the top of the specimen to provide a surcharge of 8.15 g/cm^2. This surcharge keeps the base soil from loosening during saturation and testing stages (Kwang, 1990).

Base and Filter Soil Properties

Filter Material

The filter material gradation used in this investigation is similar to the standard capping material gradation usually placed underneath the ballast layer in a railway track. Initially a silty-sandy gravel mix was sieved through various AS Standard sieves and individual particle sizes were stockpiled. The filter soil was then prepared by mixing individual sizes to a predetermined weight to achieve the field gradation as shown in Figure 1. The filter material had a density of 2.1g/cm^3 at a placement moisture content of 5%.

Base Soil

Locally available clayey silt was used as a base soil in this investigation. A typical gradation of base soil is shown in Figure 1. The base soil had a density of 1.6g/cm^3 at a placement moisture content of 15%.

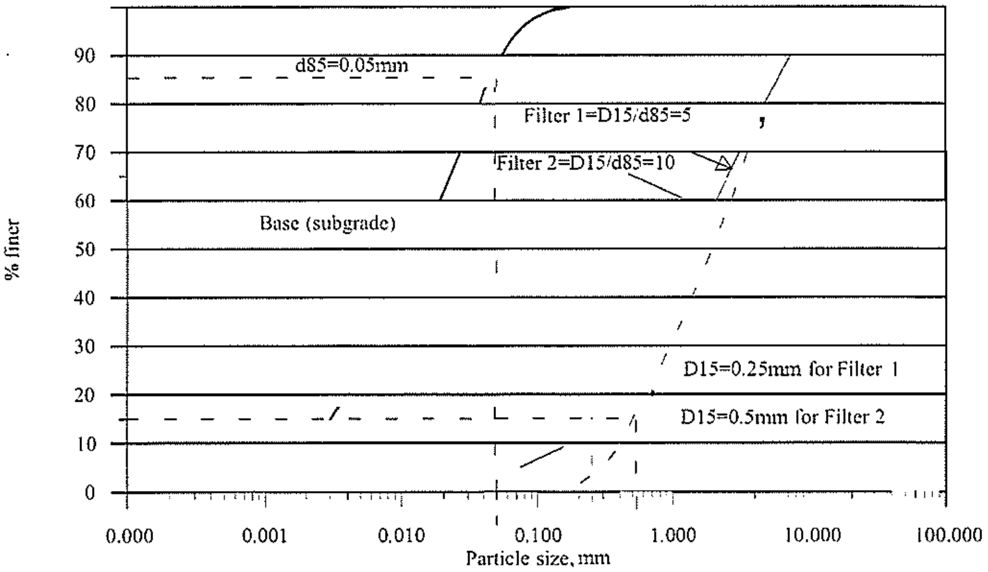

Figure 1. Base and filter soil gradation.

Test Procedure

Three tests were carried out in the laboratory using one base soil and two filter soil gradations to obtain D_{15}/d_{85} ratio of 5 and 10. The first test was conducted under a mean static pressure of 80kPa and a D_{15}/d_{85} ratio of 5. The second test was conducted on the same base-filter soil using a mean pressure of 80kPa and a dynamic sinusoidal pressure of 50kPa.

Saturation

The sample was first saturated to remove the trapped air bubbles within the sample which could affect the filtration process. A high vacuum pump was connected with the inlet valve of the cylinder and suction was applied until water from the outlet valve filled the cylinder. The outlet valve was then closed and the vacuum pump was disconnected from the inlet valve. The suction was released by opening the inlet valve. The specimen was left overnight to ensure complete saturation.

Testing Stages

The pressure distribution in the ballast bed 300mm thick beneath the sleeper was found to be approximately 50kPa. Therefore, in this investigation a static pressure (σ_{stat}) of 50kPa was applied followed by an equivalent dynamic component of 50kPa applied to the filter layer from a typical train speed of 50kph (Figure 2). Each test was continued for 2-3 days until no fines were observed to come out at the outlet end.

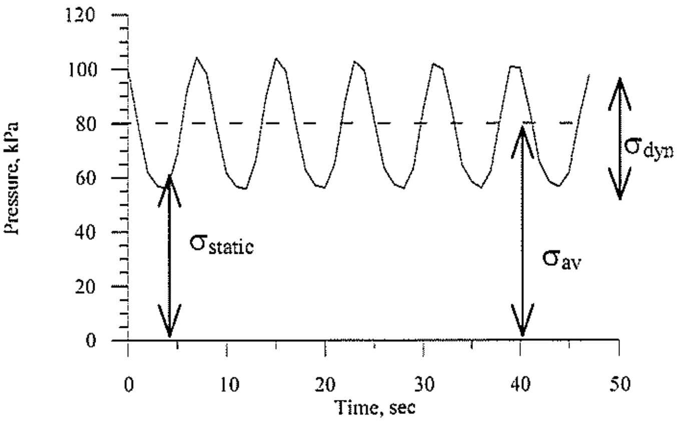

Figure 2. Typical static and dynamic loading condition used in this study.

Testing Program

The testing program was arranged in such a way that it provided some useful information on the impact of dynamic pressure on the existing filter design criteria in particular the piping ratio. Laboratory tests were carried out on two filter materials having uniformity coefficients (C_u) of **5** and 11 (Figure 1) for a given base soil, namely clayey silt (C_u = 10) collected from a local site. The filter materials were selected in such a way that they had a piping ratio, D_{15}/d_{85}, of 5 and 10. These two ratios represent the lower and upper bound values in designing filter under static conditions. For both filter materials, the coarser portions greater than 85 percentile finer particle size was kept unchanged. Three tests were carried out in the laboratory using the dynamic filter test apparatus. Test 1 and Test 2 were carried out on filter-base soils having a (D_{15}/d_{85}) ratio of 5 under both static pressure of 80kPa and dynamic pressure of 50kPa. At the end of each test, the base soil was taken out of the Perspex cylinder into 3 or 4 equal layers. The particle size distribution of each layer of base soil was then analyzed using a laser Particle Size Analyzer.

Definition of Failure

The filtration criteria can not be defined in a simple and straightforward way due to the fact of personal judgement or biases involved in the assessment. In this study, the following criteria were used to assess the filtration process:

Gradation of base soil before and after test: Base soils collected into various layers and gradations were compared with the initial gradation to assess the disturbance or loss of fines.

Visual observation: The loss of base soil and discharge were visually assessed to identify continual loss indicating 'failure'.

RESULTS AND DISCUSSIONS

Test 1

Test 1 was performed on base and filter soils having uniformity coefficients of 10 and 11, respectively. A piping ratio, D_{15}/d_{85}, of 5 was selected. A static pressure (σ_{stat}) of 80kPa was applied during this test. A very small loss of base soil and negligible amount of base settlement was observed during this investigation. The after-test gradation of each layer of base soil was determined and very little or no change was observed compared to the initial gradation (Figure 3). The settlement at the top of the base soil was also insignificant. Therefore, Terzaghi's piping ratio of 5 may be considered to be conservative for widely graded soils as previously reported by Bertram, (1943).

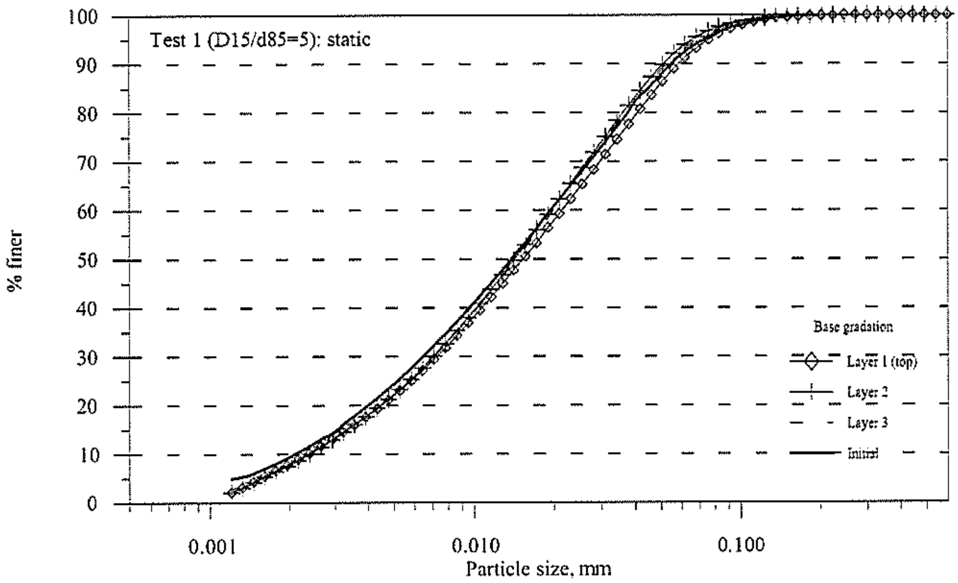

Figure 3. Base soil gradation before and after test under average static pressure for D_{15}/d_{85}=5.

Test 2

Test *2* was performed on similar base and filter soil combination as used in Test 1, however both static and dynamic pressure of 80kPa and 50kPa were applied. As expected the flow of water was higher under the peak dynamic pressure of 105kPa compared to the lowest pressure of 55kPa ie. the flow pattern also followed the trend similar to the sinusoidal applied pressure. The test was stopped after two days when no suspended fines were present in the discharged water. At the end of the test, the base soil gradations for each layer were checked and plotted in Figure 4 together with the initial gradation. It can be seen that the base soil has experienced very little or no disturbance as a result of the dynamic pressure head on top of static pressure. This could be due to the very conservative value of piping ratio, D_{15}/d_{85}, used in this test.

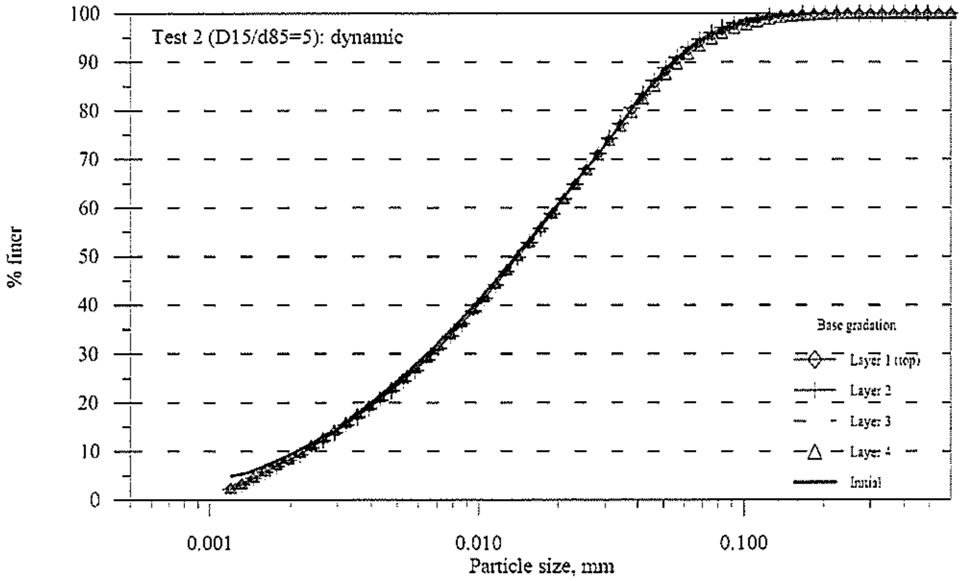

Figure 4. Base soil gradation before and after dynamic loading for D_{15}/d_{85}=5.

Test 3

Test 3 was performed on base and filter soils having uniformity coefficients of 10 and **5**, respectively. A lower value of C_u for filter soil provides less fine particles, hence greater effective pore size. The loss of base soil was observed to increase with the decrease in uniformity coefficient of filter soil under static and dynamic pressure heads. The after-test gradation of the base soil indicated significant disturbance of gradation when compared with the initial gradation of the base soil (Figure 5). The settlement of the base was found to be as high as 20% of the base height (Figure **6**). The base soil gradation also showed significant loss of fines, in particular particles smaller than d_{85} sizes. Therefore, a D_{15}/d_{85} ratio of 10 for widely graded soils may be considered too high.

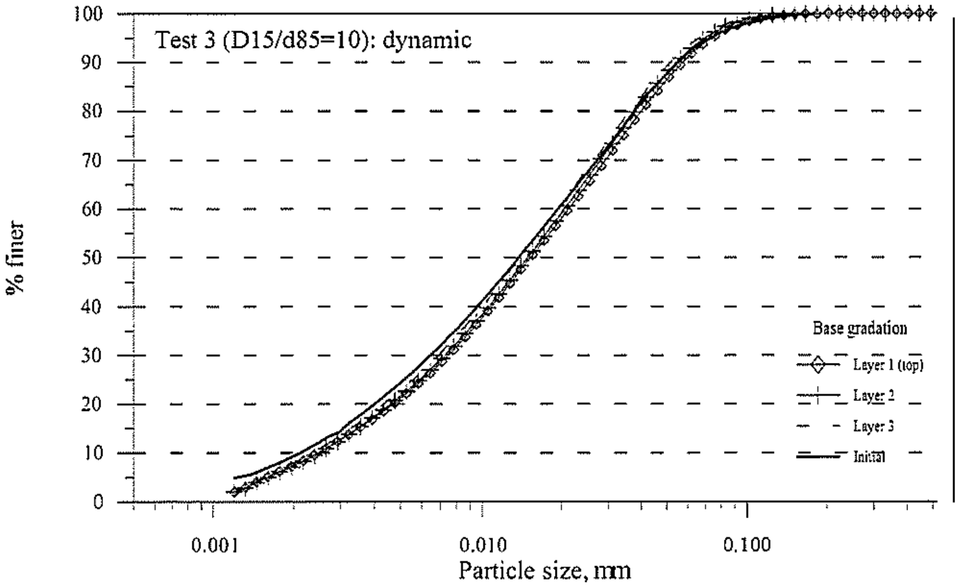

Figure **5**. Base soil gradation before and after dynamic loading for D_{15}/d_{85}=10.

Figure 6. Loss of base soil at the end of Test 3.

APPLICATION OF THE FILTER TEST RESULTS

The filter test results described in this study are applicable to railway track design where a filter material known as 'capping soil' is used at the ballast and subgrade interface. The present design guideline is based on static pressure and often results in migration of fines from the base to the top of the ballast layer thus fouling the ballast. Therefore, it is believed that the outcome of this test will significantly influence the present selection criteria for the capping material used under railway track. A series of laboratory filter tests under dynamic loading is currently underway to investigate in details the filtration behaviour of the 'capping soils'.

CONCLUSIONS AND RECOMMENDATIONS

The filter design criteria for widely graded cohesionless soils under dynamic loading are not well understood. In this study a filter test apparatus was developed to simulate the field conditions observed at the capping-subgrade interface. The laboratory filter apparatus was used to test base-filter soils having a D_{15}/d_{85} ratio of 5 and 10. The effects of both dynamic and static pressure components were tested and the following conclusions are made based on limited laboratory tests:

- The upper bound value for piping ratio, D_{15}/d_{85}. of 10 may be considered as unconservative for widely graded cohesionless base soil tested under dynamic loading. An increase in loading frequency will also increase in dynamic loading and thus greater stress will be generated within the filter soil. Therefore, a 'critical' value of piping ratio is dependent on the train speed or dynamic loading frequency. A lower value of D_{15}/d_{85} ratio could result under an increased dynamic loading frequency.

- The lower bound value of piping ratio of 5 is still believed to be very conservative for widely graded soils under both static and dynamic pressure heads.

- The finer part especially close to D_{15} size of the filter material has significant influence on the overall filtration process.

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