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# Effects of principal stress axis rotation on cyclic deformation characteristics of rail track subgrade materials

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**Abstract**

The cumulative plastic deformation of rail track subgrade materials under moving wheel loads is a complex problem. The plastic deformation and resilient modulus of subgrade materials subjected to moving wheel loads are a function of Principal Stress Axis Rotation (PSAR). Difficulties associated with the control of PSAR in conservative experimental methods lead to inaccurate estimations of the actual plastic deformation characteristics of rail track subgrade. Therefore, this study modifies a torsional multi-ring shear apparatus to evaluate the deformation characteristics of subgrade materials under moving wheel loads. The performance of this modified apparatus is evaluated by comparing the experimental results with those of small-scale model tests on an asphalt roadbed rail track with sandy subgrade. The evaluation suggests that the modified multi-ring shear apparatus has an excellent capability to estimate the deformation characteristics of rail track subgrade under moving wheel loads. A series of modified multi-ring shear tests is then conducted to investigate the effects of the loading conditions, the subgrade density, and the loading frequency on the deformation of subgrade materials under moving wheel loads. The results of these tests show that cyclic single-point load tests underestimate the actual deformation characteristics of subgrade materials irrespective of the subgrade density and the loading frequency. Furthermore, the ratio between the plastic cumulative deformations obtained from the moving wheel loading and from the cyclic single-point loading, referred to as the "ratio of axial strain" ($R_s$), is introduced to evaluate the plastic deformation characteristics of rail track subgrade materials under moving wheel loads only, using the results of cyclic single-point loading tests. Finally, an empirical formula is proposed to predict the cyclic plastic deformation of rail track subgrade materials as a function of the number of loading cycles.


*Keywords:* Rail track subgrade; Cumulative plastic deformation; Principal stress axis rotation; Modified multi-ring shear apparatus; Cyclic moving wheel load

## 1. Introduction

Cumulative plastic settlement, a type of rail track mechanism, can critically impact both the design life and the maintenance costs of a rail track. Current guidelines provide no reference to the cumulative plastic settlement with cyclic loadings in the design of new rail tracks, except for the Li and Selig (1998) design method (Burrow et al., 2011; Dareeju et al., 2014). They accounted for the number of cumulative loading cycles within the lifetime of a rail track in estimating the ballast layer thickness to prevent subgrade progressive shear failure and excessive plastic deformation. However, conventional experimental methods, such as cyclic triaxial and California bearing tests, outlined in all current design guidelines, including those by Li and Selig (1998), are unable to replicate the actual stress

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state of subgrade under moving wheel loading conditions due to difficulties in controlling the principal stress axis rotation .

The change in the principal stress axis of a given soil element with the position of the train wheel is the definition of principal stress axis rotation (PSAR). Miura et al. (1986), Brown (1996), and Ishihara and Towhata (1983) showed the influence of PSAR on the cumulative plastic deformation of coarse grained materials. The results of laboratory experiments (Gräbe and Clayton, 2009; Powrie et al., 2007), small-scale model experiments (Hirakawa et al., 2002; Momoya et al., 2005), numerical investigations (Powrie et al., 2007; Yang et al., 2009), and field investigations (Burrow et al., 2007; Gräbe, 2002) further highlight the influence of PSAR on the cumulative plastic deformation characteristics of rail track subgrade. Higher costs, difficulties in controlling the loading conditions, restrictions and strict policies, and the lack of available data highlight the need for a simple test approach for replicating the actual stress state of rail track subgrade under moving wheel loading conditions.

Ring shear apparatuses are widely used to estimate drained strength parameters. The back analyses of landslides using these parameters have shown better agreements than reversal direct shear tests (Stark and Vettel, 1992). Both split-ring and solid-ring devices are used to measure the large displacement shear resistance of sands (Sadrekarimi and Olson, 2009; Stark and Vettel, 1992). In ring shear apparatuses, however, the applied normal stress can decrease during consolidation and shear with increments in the apparent shear resistance of the specimen due to wall friction between the specimen and the confining rings (Hvorslev and Kaufman, 1952). Although this friction error can be minimised using a wider specimen, this increases the vulnerability of the strain rate effect (Sadrekarimi and Olson, 2009). As vertical stress relief or a reduction in wall friction depends on the relative movement between the soil and the confined rings, the wall friction is not mobilised at the middle of wider specimens during consolidation or shearing. Therefore, researchers in the past have explained the suitability of ring shear apparatuses for measuring the shear strength properties at large displacements, since the progressive failure phenomenon is irrelevant at this condition (Hvorslev, 1939). Considering these facts, Ishikawa et al. (2011) modified a conventional spilt-ring shear apparatus with multi-rings so that both torsional cyclic shear and cyclic vertical stress could be simultaneously applied on a soil specimen to simulate PSAR. Ishikawa and Miura (2015) and Inam et al. (2012) used this apparatus to evaluate the influence of PSAR and the water content on the plastic deformation behaviour of the base/subbase granular materials of both rail tracks and road beds. However, this apparatus is unsuitable for use with subgrade materials, which are much finer than base/subbase materials, as the fine particles go through and get trapped between the rings.

This paper presents further modifications to the multi-ring shear apparatus developed by Ishikawa et al. (2011), so that subgrade materials can be tested for plastic deformation under moving wheel load conditions. The performance of this modified apparatus in estimating the plastic deformation of subgrade materials is then verified using the results of small-scale model tests on a rail track subjected to moving loads. Furthermore, a series of modified multi-ring shear tests is conducted to investigate the effects of PSAR, the loading frequency, and the density of the materials on the plastic deformation of rail track subgrade. Finally, an attempt is made to estimate the cyclic plastic deformation of subgrade materials using conventional cyclic single-point loading tests, which are common and easy to perform.

## 2. Test apparatus

The multi-ring shear apparatus, developed by Ishikawa et al. (2011) with modifications and adopted in this study, is shown in Fig. 1(a). The apparatus can accommodate a hollow cylindrical soil specimen with a height of 100 mm, an inner diameter of 120 mm, and an outer diameter of 240 mm. The cylindrical surfaces

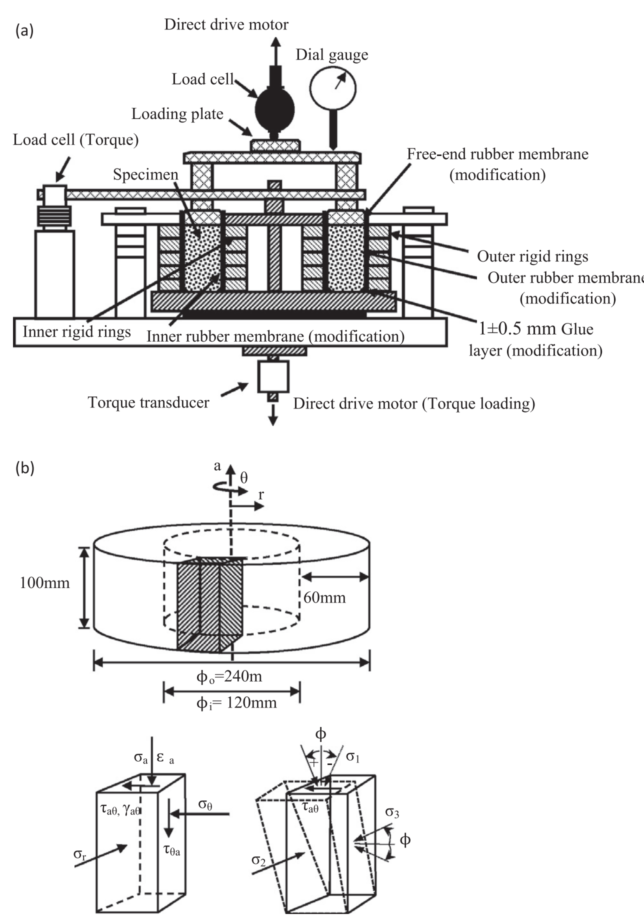


Fig. 1. Modified multi-ring shear apparatus: (a) schematic diagram and (b) stress-strain definition for soil specimen.