EXPERIMENTAL STUDY ON YIELDING AND PLASTIC FLOW OF TOYOURA SAND

Institute of Industrial Science, University of Tokyo, Student Member. ○1. Catherine Kariuki
Institute of Industrial Science, University of Tokyo, Fellow Member. 2. Reiko Kuwano

1.INTRODUCTION AND OBJECTIVE OF STUDY

Plasticity theory has over the years been extended to explain the complex problems associated with deformation of geo-materials. The works of Drucker et. al. in the 1950's forms the earliest works of describing the behavior of geo-materials using elasto-plastic theory, over the years many types of elasto-plastic constitutive models have been proposed. In general, elasto-plastic theory consists of yield functions, plastic potentials and hardening rules. Yielding is generally associated with end of linear-elastic range although it has been loosely defined as the point at which the stress-strain or stress-energy curves show a sudden change of slope. Multiple yield Loci, provide a more descriptive pre-failure soil behavior and is made up of two mobile (Y1~Y2) sub-yield surface and two less easily modified outer yield surface (Y3-Y4) as has been proposed by Mroz and Jardine. Kuwano R. (1999), developed similar multiple yield loci for Ham river sand. To properly describe the yielding behavior of Toyoura sand, the first objective of this study will be to establish the kinematic yield loci of medium dense isotropically consolidated Toyoura sand following the definitions of Kuwano R. (1999).

The plastic potential is another important component of a constitutive model and it defines the direction of plastic strain increments, the plastic strain increments are given as outward and perpendicular to the plastic potential. Unlike elastic strains, plastic strains increment vectors aren't governed by the stress increment but by a particular combination of stress at the particular point in the stress space. Normality or associated flow is commonly assumed due to its ease in computation. In associated flow rule, the plastic potential coincides with the yield loci, hence a reduction in the number of functions required in specifying a soil model. Wood M. D. (1990) observed normality from data by Graham, Noonan, and Lew (1983) on Winnipeg clay with a variation of +/-20°. But, for sands he observed normality was not valid and that assuming normality would result to greater negative plastic volume strains than would actually be observed. he goes further and proposes several plastic potential functions for sand and concludes that normality holds for clay.

Yong N. R. & Mohamed O. A. (1984), by undertaking true triaxial test on kaolin, observed that the plastic strain increments weren't normal to the yield surface, hence discounting normality. Al-Sharrad M. A. et al. (2017), for unsaturated isotropically and anisotropically compacted Spewshite kaolin specimens, observed normality with minimal variation in both isotropic and anisotropic compacted samples and with constant and varying suction. Kuwano (1999), observed that although sand was generally, thought to follow non-associated flow rule, this was only the case in the larger strains that is Y3-loci, but in the lower strains loci Y1 & Y2, associated flow rule was valid. The availability of adequate experimental proof to validate flow rules for varying conditions and types of soil and at different stages of yielding is not clearly understood. Hence, the second objective of this study was to experimentally establish the plastic flow rule of medium dense Toyoura sand, by undertaking several stress path tests.

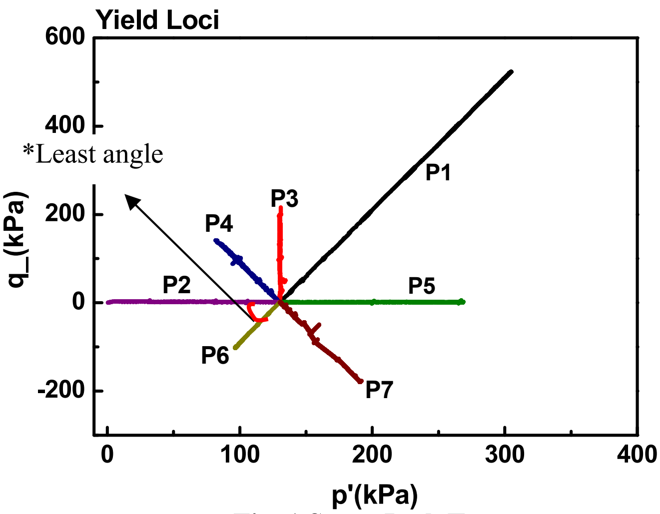

Fig. 1 Stress Path Tests.

2. METHODOLOGY OF STUDY

By air pluviation, identical samples of Toyoura sand, void ratio 0.72~0.74 were prepared, saturated and consolidated isotropically to a P' value of 130kPa. The samples were then sheared following the paths: $-\Delta\sigma'_v$ –P6, $+\Delta\sigma'_v$–P1, $+\Delta q$–P3, $+\Delta p'$–P5, $-\Delta p'$–P2, and mirror of paths $+/-\Delta\sigma_v$ –P4 and P7 respectively in the stress space. Refer to Fig.1. During both shearing and consolidation, multiple wave and small cycle measurements were taken by creeping at predetermined intervals for a duration of 15 minutes. The elastic stiffness measurements were used to determine the elastic strains. From the data the kinematic Yield Loci: Y1, Y2, Y3 and Y4 were established following the definition by Kuwano R. (1999).

Y1 is defined as the loci enclosing the predominantly elastic region and was determined as the point at which the plot of axial stress and axial strain deviated from initial tangent. Y2 was defined as the loci enclosing a region where some local yield is occurring but the whole packing is still elastic. It is identified as the point at which the direction of change in shear strain invariant($\boldsymbol{\varepsilon}_s$) to that of change in volume strain($\boldsymbol{\varepsilon}_{vol}$) occurs. Y3 is the loci that represents large scale yielding and is identified as the point at which there is a sharp change in the slopes of stress-strain curves. While Y4 is the phase transformation line. See Fig. 2. Contours of the ratio of axial plastic strains to that of axial total strains were plotted and at each point the vector of total strains increment was plotted as shown in Fig. 3 to determine the flow rule. Al-Sharrad M. A. et al. (2017), observed that beyond the Loci Y2 the plastic strains are dominant and influence the strain vector,

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Contact address: 4-6-1-Bw 305, Komaba, Meguro-ku, Tokyo, 153-8505, Japan, Tel: +81-80-3722-8056

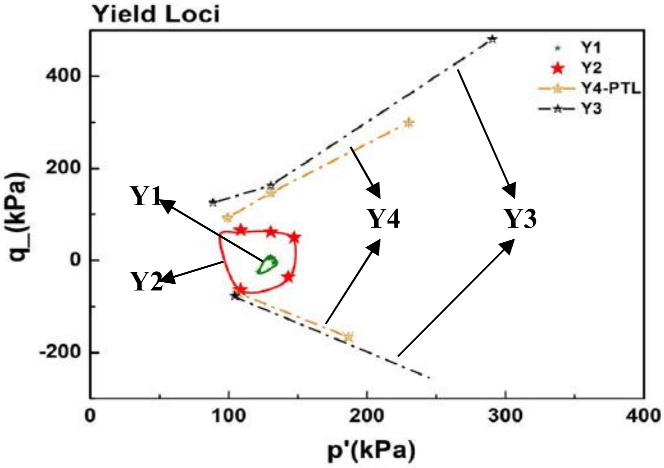

Fig. 2 Multiple Yield Loci. OCR=1, Toyoura sand

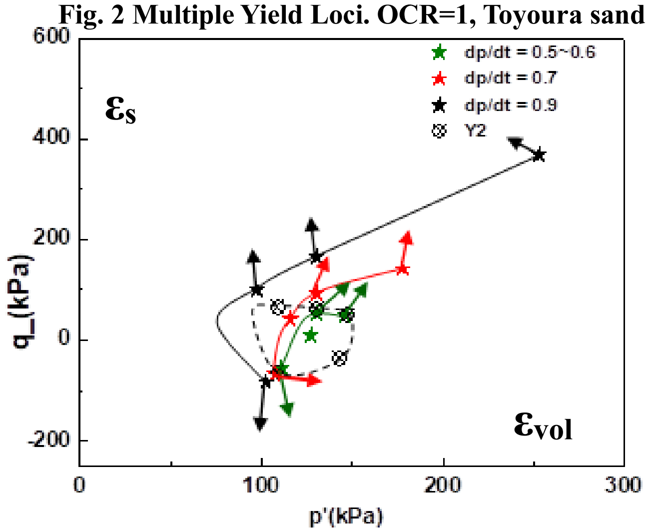

Fig. 3 Plastic Potential. (Toyoura sand)

Kuwano R. (1999), had observed that the ratio of plastic strains for Y2 was always equal or more than 0.5. Hence to understand the flow rule followed by medium dense Toyoura sand on triaxial stress conditions, total strain vectors were plotted on contours of strain ratios starting from ratio 0.5.

3. RESULTS AND DISCUSSIONS

From Fig. 2 the plot of the Yield loci for the probe tests on medium dense Toyoura sand, it is observed that Y1 & Y2 are affected by the recent stress history, as creeping effects were minimal. Y1-Y2 are observed to elongate towards the direction with the least angle from the path of the previous stress: P6 as indicated in Fig.1. Similar results were obtained by Kuwano (1999), as illustrated in Fig. 4 below. Kuwano (1999) had observed that Y2 corresponded with a ratio of plastic strains to total strains of 0.5. In this study, different paths have different ratios, with those in the compression side being 0.5~0.6 apart from P4 and those on extension side >0.7. As observed by Al-Sharrad M. A. et al (2017), the strain vector is predominantly influenced by elastic strains within Y1 and Y2, assuming total strain vector to being comparable to the plastic strains vector would be invalid. Hence, the strain vectors were only plotted from Y2 and on contours of the ratio of plastic axial strains to total axial strains as shown in Fig. 3. The vectors are rotated and not normal to the contours. Indicating that from the Y2 surface the non- associated flow rule holds. Kuwano (1999), had similar observations on tests conducted on Hime sand. Additionally, she observed that in the Y1 loci, the associated flow rule was applicable but rotation of the vectors was observed from Y2. It should also be noted that the shapes of the plastic strain to total strains contours were different to those of the Yield Loci and were highly influenced by the loading direction. Furthermore, it was found that the contours of incremental strain energy at the smaller values are similar in shape to the Y1 and Y2 while the contours of total strain energy at the larger energy levels are similar in shape to Y3. Kuwano (1999), summarized the works of previous researchers that suggested the usage of total strain energy as parameter to determine the large scale yielding(Y3&Y4) and incremental strain energy to determine the Y1 & Y2. Which could be concluded as a result of the predominant strains in the regions (Regions enclosed by Y1 & Y2- elastic strains and Y3 & Y4 plastic strains).

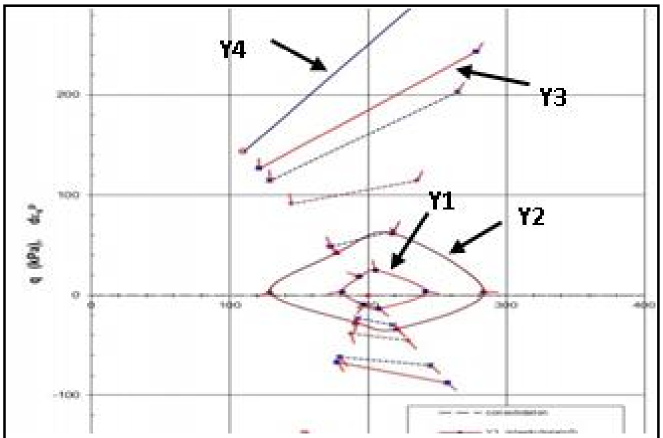

Fig. 4 Yield Loci, Ham River sand. OCR=2 on the q-p' plane. Source: Kuwano (1999).

4. CONCLUSION

The objective of this study was to establish the kinematic yield loci of Toyoura sand, by considering medium dense Toyoura sand and shearing it following several stress path the kinematic yield loci were determined about the probe point. The associated flow rule commonly used due to its ease in computation was observed to be experimentally invalid from the Y2 yield loci where the ratio of plastic strains to total strains is generally greater than 0.5. This is in agreement with the literature review, although it should be noted that Kuwano (1999) observed that for conditions below Y2 the associated flow rule was valid.

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