Rate effects at varying strain levels in fine grained soils

Effets de vitesse de déformation à niveaux de déformation variant en sols à grains fins

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ABSTRACT: There is a need for an improved understanding of rate effects over a wide range of strain rates in order to improve the modelling and analysis of high strain rate activities. Using triaxial testing on reconstituted kaolin over a wide strain rate range this paper examines the impact of strain rate on the aspects of soil response which are important in many areas of geotechnical engineering. It is demonstrated that shear strength, small strain stiffness and the elastic shear strain threshold are rate dependent.

RÉSUMÉ : Il est besoin pour une meilleure compréhension des effets la vitesse de déformation sur une grande gamme de vitesses de déformation en vue d'améliorer la modélisation et l'analyse des activités à vitesses de déformation haute. Par l'utilisation tests triaxiaux sur kaolin reconstitué sur une grande gamme de vitesses de déformation, présent document examine l'impact de vitesse de déformation sur les aspects de réponse du sol qui sont importants dans nombreux domaines d'ingénierie géotechnique. Il est démontré que résistance au cisaillement, rigidité à faible déformation et seuil de déformation élastique sont dépendant la vitesse de déformation.

KEYWORDS: rate effects, strain rate, strain level, small strain, elastic strain threshold, shear modulus, dynamic tests, triaxial, kaolin

1 INTRODUCTION

Rate effects are an important consideration in many areas of geotechnical engineering as they influence the strength and stiffness of the soil, however, the impact of rate effects is difficult to determine and analyse. Because of this, there is a need for a better understanding of rate effects and how they influence soil response.

One aspect that requires further study in order to achieve this is the relationship between rate effects and strain level, as this varies throughout the course of geotechnical activities. Being better able to consider rate effects throughout the entire strain range raises the opportunity to improve both accuracy and efficiency.

This paper considers the strain-rate dependence of rate effects over a wide range of strain magnitudes at shear strain rates from 0.333 to 60,000 %/hr.

1.1 *The influence of strain rate*

The most commonly used assumption in terms of rate effects is that of Kulhawy and Mayne (1990) which states that for every log cycle (tenfold) increase in strain rate, a ten percent increase in shear strength is expected. However, this has been shown to be variable, with the rate effects observed ranging from 9.5 to 20 % (Bea 1982). Another key consideration is that this assumption does not consider any variation of rate effects with strain level (Brown 2009), as it is based on a correlation using only peak shear strengths. Similarly, only undrained testing was used, meaning that the impact of drainage on the determination of the rate effect was not dealt with.

Drainage effects are significant as the strain rate influences whether there is time for drainage to occur. This means that rate effects tend to follow a "U-shaped" curve as shown in Figure 1. At extremely slow rates, there is time for pore pressure developed during shearing to fully dissipate. As the strain rate increases, the reducing time for drainage means that increasing pore pressures and hence lower shear strengths are observed in the partially drained region. As the strain rate is increased further, the soil response becomes almost fully undrained, where pore pressures are at their maximum. After this point, viscous effects cause the observed shear strength to increase with strain rate up to a potential viscous limit (Chow and Airey 2011). The form of this shear strength-strain rate relationship has been verified by studies using a wide range of test methods from cone penetrometer testing to large scale shear boxes. (Steenfelt 1993, Lehane et al 2009)

Shibuya et al (1996) showed that the initial small strain stiffness, E_{max}, is rate independent and constant for the range of strain rates investigated (0.6 to 84 %/hr). It was also found that this linearity continued up to a strain defined as the elastic strain threshold, ε_{EL}, which was itself rate dependent, increasing with increasing strain rate. These findings were confirmed by Mukabi and Tatsuoka (1999).

Lo Presti et al (1996) found that soil stiffness is rate independent below 0.001 % shear strain, and increases with strain rate beyond this point. To allow comparison of relative stiffnesses at different strains and strain rates, Lo Presti et al (1996) defined the strain rate coefficient, α.

There are numerous geotechnical applications where rate effects are an important consideration, including free falling penetrometer tests where velocities can reach up to 12 m/s

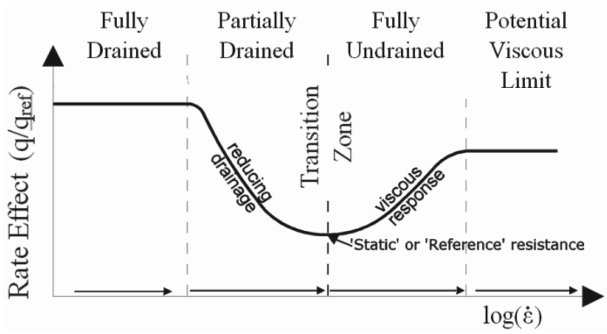

Figure 1. U-shaped curve showing the idealised variation of rate effect with strain rate (Quinn and Brown 2011)

(Chow and Airey 2011) and Statnamic pile tests (Brown and Hyde 2008) where the pile is displaced at rates of the order of 1 m/s. In these cases, rate effects cause the capacities derived from the tests to exceed static values; an issue which is usually dealt with by the inclusion of damping co-efficients in the analyses. (Brown and Powell 2013) These damping co-efficients are not always uniform throughout each test, but may vary with strain level. This highlights the importance of understanding the strain level dependence of rate effects in order to improve the accuracy of dynamic testing in the field.

2 MATERIAL TESTING AND PROCEDURES

The tests were carried out on reconstituted speswhite kaolin, the properties of which are shown in Table 1.

Table 1. Properties of the speswhite kaolin used

Property	*Value*
Plastic limit, w_P (%)	32.5
Liquid limit, w_L (%)	65.0
Plasticity index, PI (%)	32.5
Clay fraction (%)	80
Activity (%)	40.6
Specific surface area (m^2/g)*	36.7
Permeability, k (mm/s)#	1.17×10^{-6}
c_v (m^2/year)+	23.52
MCSL	0.9
λ	0.101
N	2.678

* Determined from methylene blue spot testing
\# Determined at an effective stress of 300 kPa
\+ Determined for a 100 kPa stress increment

The samples were first prepared as slurry with a moisture content of 120 % using de-aired, de-ionised water before being one dimensionally consolidated to an effective stress of 180 kPa for three days. These were then trimmed to 200 mm length and 100 mm diameter to create triaxial samples. Once installed in the triaxial apparatus, the sample was saturated to an effective stress of 50 kPa at a back pressure of 300 kPa and then reconsolidated to an effective stress of 300 kPa to restore isotropic conditions. Sample drainage was facilitated by using vertical filter paper drains on the surface of the sample, connected to both the top and bottom drainage valves. These were required as the use of lubricated end platens in the testing meant that conventional drainage was not possible, and had the additional benefit of significantly reducing consolidation times.

2.1 *Testing apparatus*

The tests were carried out in a GDS advanced electromechanical dynamic triaxial rig specially modified to carry out high speed monotonic tests. The rig is capable of axial displacement rates of 100 mm/s, and during high speed testing it is controlled by a GDS digital system capable of controlling the axial displacement within a time interval of 0.1 milliseconds. Both the back and cell pressures were provided by GDS pressure controllers. Lubricated end platens of a similar design to those proposed by Rowe and Barden (1964) were used in order to minimise the inhomogeneity caused by end restraint conditions. As these can introduce errors into the measurement of small strains using external methods, these were measured using Hall effect transducers, two axial and one radial, mounted directly on the sample providing a resolution of 1×10^{-6} % strain. Pore pressures were monitored using a mid-height pore pressure transducer mounted on the surface of the sample.

2.2 *Testing programme*

The testing programme consisted of triaxial tests at shear strain rates from 0.333 to 60,000 %/hr in order to investigate strain rate effects over as large a range as possible. These were carried out at a comparatively low effective stress of 300 kPa as previous studies have shown that greater rate effects are observed at higher moisture contents. (Bea 1982, Brown and Hyde 2008, Chow and Airey 2011) Throughout the testing programme, the samples were allowed to drain through the filter paper drains in order to allow rate effects due to consolidation to be investigated.

3 RESULTS AND DISCUSSION

3.1 *Observed rate effects and their modelling*

The rate effects observed at the various strain rates are shown in Figure 2, with a shear strain rate of 100 %/hr taken as the reference rate. In order to allow comparison with other studies using differing materials and sample sizes, the strain rates have been converted into the normalised dimensionless velocities used by Randolph and Hope (2004) as shown in Equation 1.

$$V = \frac{vd}{c_v} \tag{1}$$

where V is the normalised dimensionless velocity, v is the strain rate applied (in m/year), d is the sample diameter (in m) and c_v is the co-efficient of consolidation in m^2/year. As can be seen, the curve follows the behaviour expected with time for consolidation effects dominating up to V = 11, after which undrained viscous effects are significant.

In order to quantitatively assess the data, the rate effects model proposed by Randolph and Hope (2004) shown in Equation 2 has been fitted to the data using least mean square regression.

$$\frac{q}{q_{ref}} = \left(1 + \frac{b}{1 + cV^d}\right)\left\{1 + \frac{\lambda}{ln(10)}\left[sinh^{-1}\left(\frac{V}{V_0}\right) - sinh^{-1}\left(\frac{V_{ref}}{V_0}\right)\right]\right\} \tag{2}$$

where b, c, and d are curve fitting parameters used to model the time for consolidation effects and λ is the rate effect per log cycle increase in strain rate used to model viscous effects. V_{ref} is the normalised velocity associated with chosen reference rate and V_0 is the point after which time for consolidation effects are negligible. This process was also repeated for the measured rate effects at selected strains to identify the variation in rate effects at different strain levels as shown in Figure 3. The parameters obtained from the curve fitting process are shown in Table 2.

The fitting parameters at peak strength (which occurs at varying strain levels) show that the rate effect per log cycle was found to be 22.5% which is higher than previous studies. This highlights the need to develop a framework to predict rate effects based on the current soil state and properties of the material in question.

Table 2. Parameters used to fit the model by Randolph & Hope (2004) to the data at each shear strain level

Property	*0.17%*	*0.33%*	*0.67%*	*1.67%*	*2.67%*	*Peak*
b	0	0	0.153	0.505	0.888	1.387
c	26.52	25.55	24.61	23.11	23.53	25.09
d	1.865	1.859	2.163	2.589	2.556	2.309
λ	0.275	0.251	0.244	0.212	0.181	0.225
V_0	18.17	21.08	17.76	14.10	6.81	23.39
V_{ref}	11.17	11.17	11.17	11.17	11.17	11.17

3.2 *Strain level dependence of rate effects*

Figure 3 shows that in the partially drained domain rate effects increase with strain level, which is intuitive as at greater strains there will be more time for consolidation to occur. Additionally, at the point at which the transition to undrained behaviour occurs, the rate effects were found to be relatively independent of the strain level. Beyond this point the rate effect per log cycle reduces from 27.5 % at 0.17 % shear strain to 18.1 % at 2.67 % strain, indicating that undrained rate effects reduce with strain level, which is important in areas such as rapid load pile testing (RLT) and assessment of static pile working loads.

Lo Presti et al (1996) developed a method for comparing rate effects at different shear strain levels by defining a strain rate coefficient, α (Equation 3). This is the change in shear modulus at a given strain over the log cycle increase in shear strain rate normalised by the shear modulus at a reference shear strain rate.

$$\alpha(\gamma) = \frac{\Delta G(\gamma)}{\Delta(\log(\dot{\gamma})).G(\gamma, \dot{\gamma}_{ref})} \quad (3)$$

This method was used to further investigate the apparent dependence of rate effects on strain level. Figure 4 shows the variation of the strain rate co-efficient, α, with shear strain for the shear strain rates considered. This confirms the earlier findings that for rates where there is time for consolidation, the rate effects observed increase with increasing strain. Similarly, the rate effects reduced with strain for the undrained tests. However, the graph highlights a significant difference in the strain rate co-efficient between the partially drained and undrained tests at extremely small strains.

3.3 *Small strain behaviour*

To further investigate the effect of strain level on rate effects the small strain data from the Hall effect transducers was examined. Figure 5 shows the variation of the shear modulus, *G*, for each of the rates. Of particular interest is the fact that the initial small strain shear modulus, G_0, appears to vary with shear strain rate, reducing according to the correlation shown in Figure 6. One possible explanation for this is that at slower rates, there is more time for sample drainage at a micro-scale, causing an increase in the shear modulus at low shear strain rates. However, this does not explain the increased initial strain rate co-efficient at low strains in the fast tests.

Figure 7 shows the variation of the elastic shear strain threshold and this confirms that as found by Mukabi and Tatsuoka (1999), the elastic shear strain threshold increases with rate. A best fit was applied to this data and found that for the soil properties and stress conditions used, γ_{EL} varies as in equation 4.

$$\gamma_{EL} = 0.003\,\dot{\gamma}^{\,0.2} \quad (4)$$

Considered in conjunction with Figure 5, this shows that at the initial strain levels considered in Figure 4 (γ = 0.2 %), the faster tests exhibited a greater stiffness than the slower rate tests, explaining the discrepancy in the initial values of the strain rate coefficients. This is due to the delay in stiffness degradation caused by the increase in the elastic shear strain threshold.

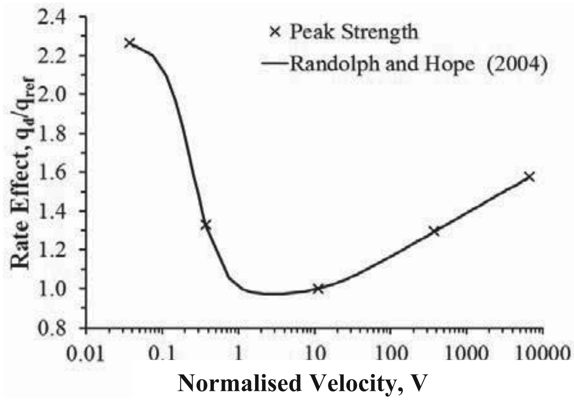

Figure 2. Graph of rate effect against normalised velocity at peak strength with the model by Randolph and Hope (2004) using a shear strain rate of 100%/hr as the reference rate

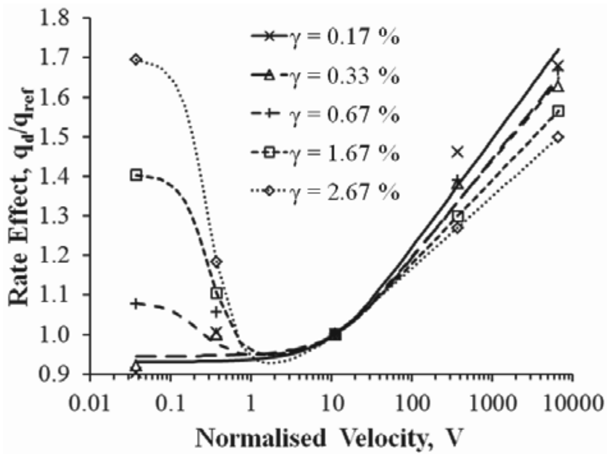

Figure 3. Graph of rate effect against normalised velocity at various shear strain levels shown with the model proposed by Randolph and Hope (2004)

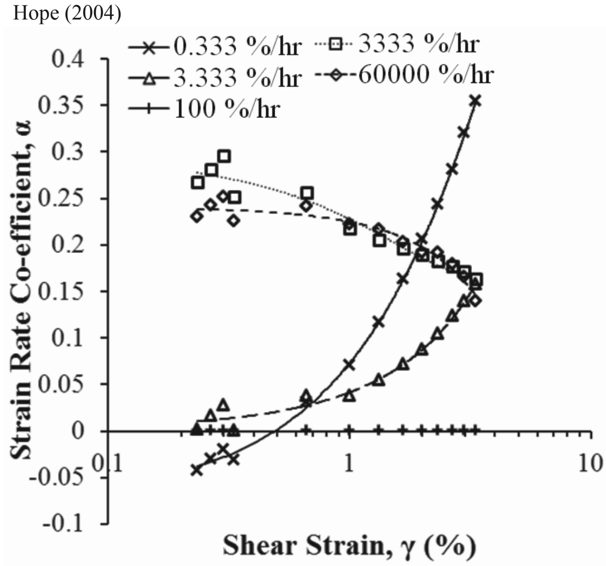

Figure 4. Graph of strain rate co-efficient against shear strain for various shear strain rates using a shear strain rate of 100 %/hr as a reference

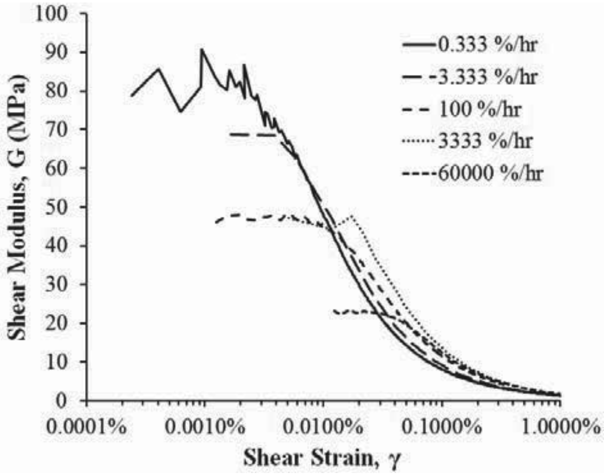

Figure 5. Graph of shear modulus against shear strain for various shear strain rates from Hall effect small strain transducer data

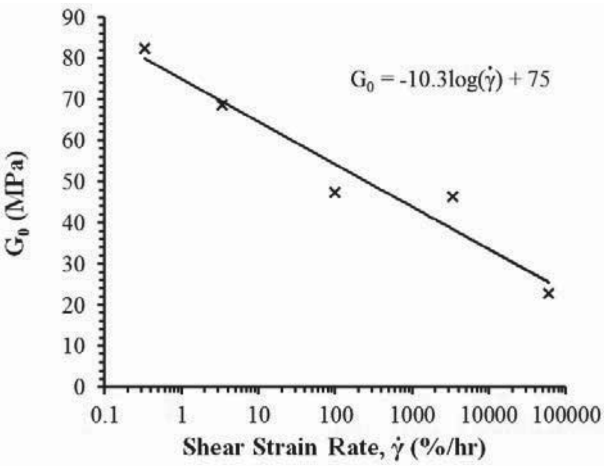

Figure 6. Graph of G_0 against shear strain rate

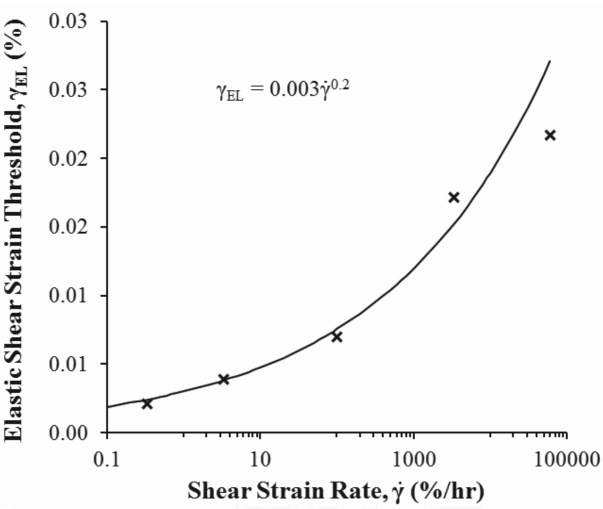

Figure 7. Graph of elastic shear strain threshold against shear strain rate

4 CONCLUSIONS

Based on triaxial tests on reconstituted kaolin at strain rates over more than 5 orders of magnitude, it has been shown that rate effects have numerous effects on the response of the soil, ranging from increased deviatoric strength to changes in small strain behaviour which are strain level dependent.

a) Peak strength rate effects in the partially drained domain have been shown to be greater than undrained rate effects due to time for consolidation.
b) The undrained rate effects observed have been shown to be higher than those reported by other studies at 22.5% per log cycle for peak strength.
c) The importance of strain level in relation to rate effects has been highlighted, with rate effects increasing with strain when partially drained and reducing with strain when undrained.
d) The applied strain rate was found to have a significant impact on the small strain response, with the elastic shear strain threshold, γ_{EL}, increasing with rate and G_0 appearing to reduce with rate.

It is hoped that the results and discussion in this paper will be of use in rate effect analysis and in the associated applications.

5 ACKNOWLEDGEMENTS

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