Plastic compression of sands due to grain crushing under high pressure

Takashi Matsushima[1], Kohei Yamashita[2] and Yasuo Yamada[3]

[1]Faculty of Engineering, Information and systems, University of Tsukuba
1-1-1, Tennodai, Tsukuba, Ibaraki 305-8573, JAPAN
tmatsu@kz.tsukuba.ac.jp

[2]Graduate School of Systems and Information Engineering, University of Tsukuba
1-1-1, Tennodai, Tsukuba, Ibaraki 305-8573, JAPAN
s0811270@u.tsukuba.ac.jp

[3] Faculty of Engineering, Information and systems, University of Tsukuba
1-1-1, Tennodai, Tsukuba, Ibaraki 305-8573, JAPAN
yamada@kz.tsukuba.ac.jp

Unconsolidated geomaterials such as sands and clay can be irreversibly compacted and densified under compressional loading. This behavior influences various geotechnical applications such as pile driv-ing, land reclamation, liquefaction countermeasure, rock avalanches and so on. As the simplest case, quasi-static one-dimensional consolidation has been studied extensively for decades (Terzaghi et al., 1996), and nowadays its analytical method is well established based on, so called, e-log p curve. However, the physical interpretation of e-log p relation in terms of micromechanical processes has not been clarified yet.

In the case of plastic compaction of sand under high compressional loading, grain crushing is a primary microscopic mechanism. In the present study, we explore the relation between the plastic compression and the evolution of grain size distribution (GSD) observed in a series of one-dimensional compression tests of dry Toyoura sand, which includes two different initial void ratios, two different loading speed, and several different loading histories as shown in Table 1 (Yamashita 2014).

It was found that the obtained e-log p curves fits well not only to the classical bi-linear model but also to the model proposed by Matsushima and Watanabe (2013) based on the Hugoniot equation of motion (Figure 1). Since the void ratio cannot be negative, it is natural that the plastic compaction regime in e-log p plot is not linear but gradually approaching an e=0 line. Therefore, under high pressure region, M-W model. Moreover, M-W model provides with a unified expression for plastic compression of sand in a wide range of strain rate; from quasi-static to very fast impact loading.

We confirmed that the grain crushing occurs after so-called ‘yield stress’ which describes the kink point in the classical bi-linear model (Figure 2). This yield stress is also described by parameter s_S in M-W model.

We plotted the evolution of grain size distribution by two types of plots; one by normal scale plot (Figure 3) and the other by log-log plot (Figure 4). The former indicates that the initially well-sorted grains tend to be broken into pieces whose size are about 1/4 to 1/5 of the original grain size. This size corresponds to the void size formed by the well-sorted granular assembly. This implies the relevance to the Apollonian packing (Borkovec et al., 1994). It is well known that the grain size distribution of the Apollonian packing has a fractal nature (Mandelbrot 1983). The latter log-log plot of cumulative number of grains against grain diameter proves that the GSDs obtained in the experiment approach to a fractal distribution. Moreover, its fractal dimension is about 2.5, which is close to that in Apollonian sphere packing, 2.47 (Borkovec et al., 1994).

Table 1 Experimental cases

Test Case	Type of Packing	Speed of Loading	Loading History (MPa)
1	Loose	Fast	0 ⇒300 ⇒0
2	Loose	Slow	0 ⇒300 ⇒0
3	Dense	Fast	0 ⇒300 ⇒0
4	Dense	Slow	0 ⇒300 ⇒0
5	Loose	Fast	0 ⇒100 ⇒0
6	Loose	Fast	0 ⇒100 ⇒0 x5times
7	Loose	Fast	0 ⇒100 ⇒0 ⇒300 ⇒0
8	Loose	Fast	0 ⇒50 ⇒0 ⇒100 ⇒0 ⇒200 ⇒0 ⇒300 ⇒0

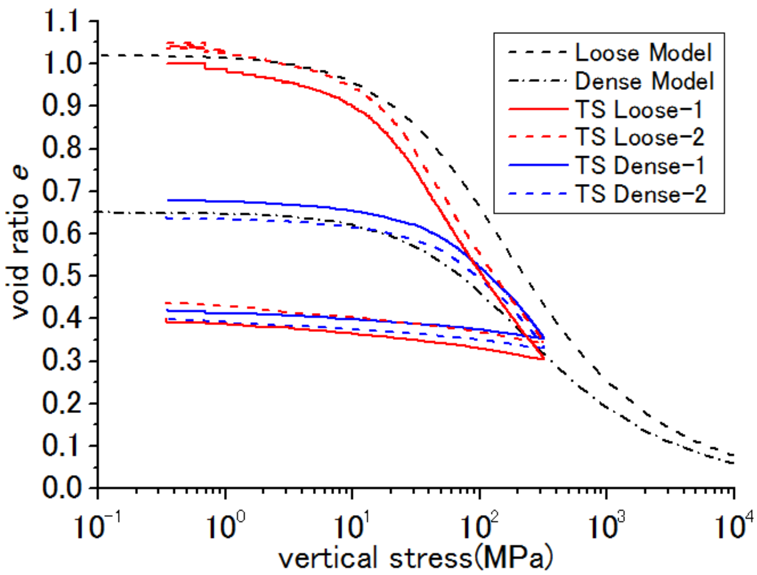

Figure 1 e-log p curve and a fitted M-W model

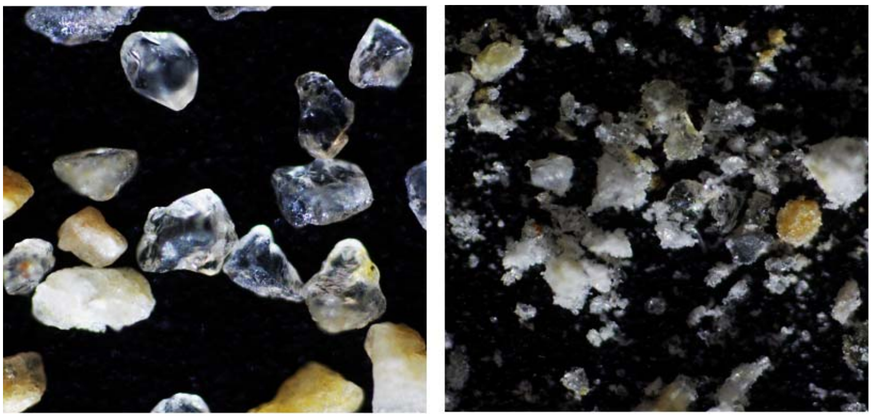

Figure 2 Microscope photos before and after grain crushing

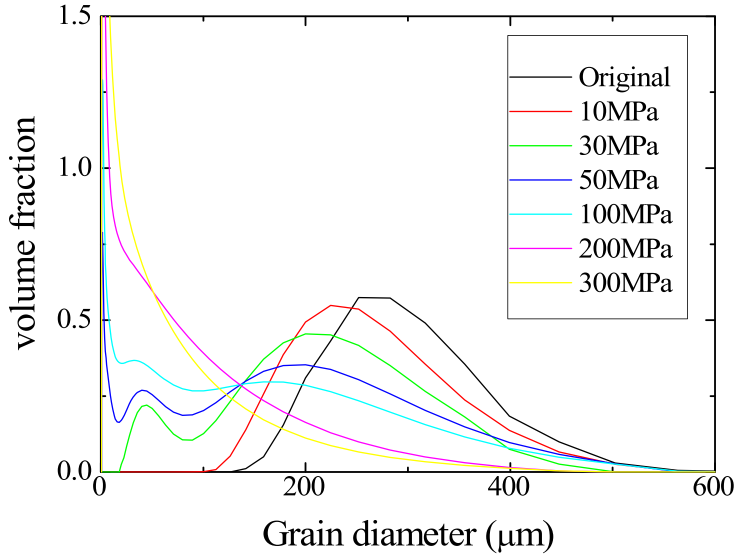

Figure 3 Evolution of grain size distribution (1): normal plot

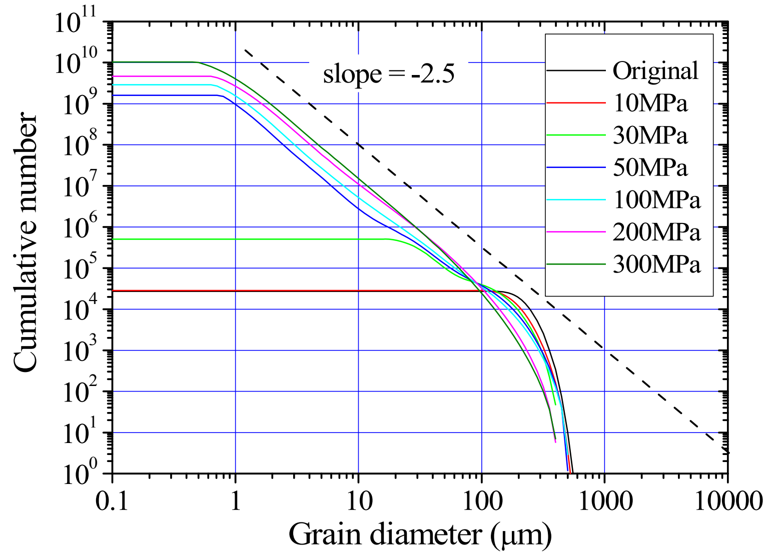

Figure 4 Evolution of grain size distribution (2): log-log plot

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