京都大学防災研究所年報　第 46 号 B　平成 15 年 4 月
Annuals of Disas. Prev. Res. Inst., Kyoto Univ., No.46 B, 2003

The Evolution of Sliding-Flow Structure under the Undrained Shearing in the Ring Shear Tests

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Synopsis

Undrained monotonic stress-controlled ring shear tests were conducted on silica sand to study the shear deformation process of granular materials. Four stages of deformation have been selected for this study namely the state between phase transformation and failure point, during the acceleration after failure, the moment the steady state appeared, and at the steady state shearing after shear displacement reached 10 m, which represent the beginning to the residual states of deformation processes respectively. Investigating the 'undisturbed' sample which collected by using a new shear zone sampler, revealed that the thickness of developed shear zone tends to increase with the progress of those stages and the shear zone could be divided into three parts i.e. the core, the adjacent zone above the core and the adjacent zone below the core respectively. At a particular final state, the shear zone has a tendency to become separated into parts of coarse and fine particles (by segregation process during steady state shearing) and finally the parallel orientation structure of the grains which correspond to the 'flow structure' was developed. This evidence is consistent with Casagrande earlier observations of flow structure. This structure is responsible to the residual behaviour of granular material. Therefore, under undrained stress-controlled test by using ring shear apparatus, the deformation process of granular material is predominantly by grain reorientation and rearrangement. If the grain crushing exist, the fine particles will be accumulated at the lower part of shear zone at residual state. Those results are very important for understanding the mechanism of rapid long runout landslides, and progressive failure on granular materials as well.

Keywords: undrained stress-controlled, deformation, shear zone, core, segregation, structure

1. Introduction

This research is concerned with the perceptive of granular materials behaviour in undrained monotonic test under stress control by using ring shear apparatus.

The deformation process on granular material is very important topic for landslide research particularly for rapid long runout type study. By knowing the evolution of the deformation processes, the mechanism of such failure could be understand, thus the prediction and mitigation to this kind of hazard for minimizing the degree of destroying and casualties could be done properly.

The stipulate of this study is based on the previous extensive research on rapid long runout landslide by means of ring shear apparatus (Sassa, 2000). Based on detail field investigation on some landslides occurred in Japan and supported by laboratory experiments by using ring shear, Sassa (1996) proposed the sliding surface liquefaction concept. This concept explained about the phenomenon of localized liquefaction on saturated dense sandy soil along the shear zone affected by grain crushing and pore pressure generation. Then he suggested that grain crushing that corresponds to the pore water pressure generation are responsible for very low apparent friction angle of granular material after failure. In consideration into account to that concept, therefore the study of shear zone development process is crucial for landslides research particularly to the rapid long runout type.

As reported by Castro (1969) that in his lecture Casagrande proposed a flow structure concept. He assumed that during liquefaction slide the relative position of the grains is constantly changing in manner which maintains a minimum resistance. Poulos (1981) based on a critical void ratio concept, proposed the steady state of deformation is that state in which the mass is continuously deforming at constant volume, constant normal effective stress, constant shear stress, and constant velocity.

In particular shear zone study, the researcher investigate the shear zone development process on granular material by using ring shear apparatus under speed control test (Mandl et al., 1977; Fukuoka, 1991) and almost all available references was considered to the drained condition by means of ring shear test (Bishop et al., 1971; Lupini et al., 1981; Wang F.W., 1998) or dry samples (Mandl et al., 1977; Fukuoka, 1991).

Mandl et al. (1977) reported the detail investigation of shear zone development process on granular material. In his research, the series of tests on various materials including sands, glass spheres, pyrex glass, and sugar were conducted by using ring shear apparatus under speed control (very slow with displacement rates between 2 and 5 mm/min) to investigate the structure development process in accordance to the geologic process (mechanics of tectonic faulting). No information about pore water pressure generation process is available in his paper.

Wang, G., and Sassa (2002) by using an intelligent ring shear apparatus (DPRI Ver.6) which allow for complete undrained test condition, reported the developed shear zone under undrained test at very large of shear displacement. The shear zone then was investigated by drainage method i.e. the water content of the specimen after test was drained through the lower part of the shear box by forcing the air through the upper drainage hose and draining water from the lower drainage valve of ring shear. Unfortunately he did not explain about the developed structure within the shear zone.

Wang, F.W., 1998 investigate the grain crushing existence by means of ring shear apparatus in relation to the excess pore water pressure generation for rapid landslide movement study. In his study he analyzed the relationship between grain crushing possibility of sand under dry test to the pore pressure generation in a saturated condition of undrained test on sandy materials, and also no information about the possibility of structural development within the shear zone.

In fact the references on undrained shear deformation processes which focused on the progression of shear zone development process on granular material by taking into consideration to its mobility (acceleration) after failure to the residual state is quit limited. More over, the structural development processes within the shear zone and the process responsible for developing shear zone on granular material are not yet understood. Indeed, these processes are very important to be known for understanding the mobility of flows and also for studying the progressive failure on granular material. Therefore by a new approached this study will try to investigate such processes.

2. Ring shear apparatus

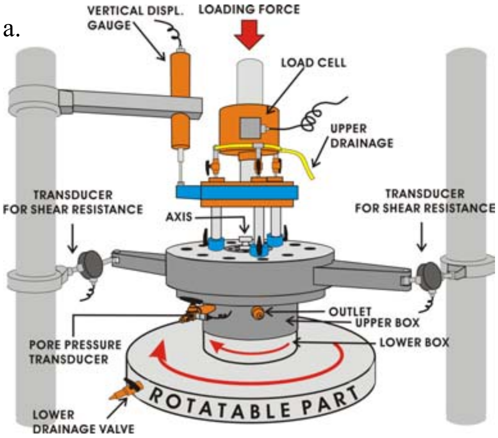
The fifth version (DPRI Ver.5) in a family of ring shear apparatuses was employed in this study. This apparatus was developed by Disaster Prevention Research Institute, Kyoto University, in 1996 (Sassa, 1997) which considered to be an intelligent, improved type as both of the satisfying criteria of the simplicity of construction and operation.

The advantages of the ring shear apparatus compared to the other devices for conducting the experiments in soil mechanics laboratory is that the ring shear apparatus could be used for carrying out the experiment on disturbed sample which allow to be sheared to very long and almost un-limited of shear displacement such as for investigating the residual behaviour as many researchers interested in (Bishop, 1971; Tika et al., 1996; Lupini et al., 1981, Wang and Sassa 2002). Other researchers investigating the strain-rate effect by means of ring shear test whether the speed of rotation (mobility) will influence the friction angle of the specimen or will not affect (Hungr and Morgenstern, 1984; Bridgwater, 1972; Sassa, 1986; Fukuoka, 1991).

The great value for this apparatus is the facility of complete undrained testing to investigate pore pressure generation before and after failure or collapse of soils (Sassa, et al., 2003). Therefore, this apparatus is the most applicable tool to reproduce the stress condition along the shear surface of the landslide in situ with very long shear displacement, then extended laboratory tests by means of ring shear test apparatus have been performed (Sassa et al., 1984, Fukuoka, 1991, and Sassa, 2000).

2.1 Structure

The sketch of the DPRI Ver.5 ring shear is shown in Fig. 1. The soil sample is set in the donut-like (circular) shear box (upper and lower boxes in Fig. 1) made of stainless at around the middle of this apparatus. The outer diameter of shear box is 18.0 cm and the inner diameter is 12.0 cm, thus the area of shear surface is approximately 141.4 cm. The specimens will be sheared with the lower half of the shear box rotated by servomotors a.



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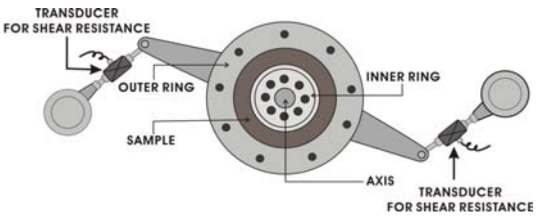
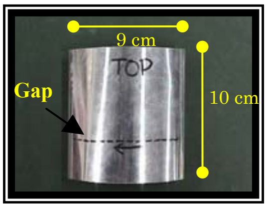


Fig. 1 Sketch of the ring shear apparatus (DPRI Ver.5) employed in this study. This apparatus was developed in 1996 by Sassa and colleagues (Disaster Prevention Research Institute, Kyoto University). a) Ring shear apparatus with all measurement devices. b) Donut likes of the sample within the ring shear boxes and the transducers for shear resistance at the left and right arms of the upper outer ring box.

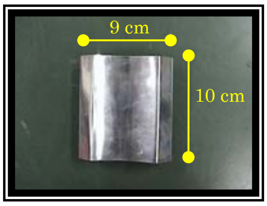
(rotatable part on Fig. 1) on the one hand, while the upper half of shear box retained by two resistance transducers, for measuring shear resistance. Both of speed-controlled test and stress-controlled test are possible. Rubber edge is bonded on the upper surface of lower half of shear box in order to prevent the leakage of water and specimen in the process of consolidation and shearing. Detail information about the structure of this apparatus is provided in Sassa (2000), and Okada (2002).

3. Shear zone sampler

In order to collect an 'undisturbed' sample from the specimen after the test, a new shear zone sampler was used. This additional tool has a total dimension of 10 cm, 9 cm and 2.2 cm for the length, wide, and thickness respectively. It made of a thin metallic aluminum of 0.03 cm of the thickness, which gives a good flexibility, easy to be formed and also to minimize the degree of disturbances of the collected sample as required for structural investigation. It also preferable material for keeping the water content of the specimen during sampling procedures.

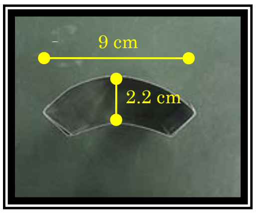


a. Front face



b. Back face

c. Permissible to be separated



d. Top viewing

Fig. 2 The over view and dimension of a new shear zone sampler for DPRI Ver.5

This shear zone sampler is permissible to be separated into 2 parts, the outer and inner part, in which have diameters of 17.6 cm and 12.4 cm respectively. The inner part has a folding flat at the both sides to hold up the outer part when they have to be combined before used (see Fig. 2 and Fig. 3.c). In order not to destroy the ring shear apparatus i.e. rubber edge, the outer and inner parts of this tool was made to have a 0.4 cm distances from each edge of the outer and inner ring of the ring shear apparatus respectively as shown in Fig. 3.b.

4. Sample characteristics

For this study the Silica Sand No.8 is selected as the sample. Silica sand is an artificial sand which made by grinding of silica sandstone with the main purpose for construction's materials. It comprises of angular and sub-angular quartz and feldspar in which quartz predominant by about 80%. The particles ranged from fine sand to silt with a specific gravity of approximately 2.65. The maximum and minimum dry densities were found to be approximately 1.494 g/cm^3 and 1.053 g/cm^3, respectively. The grain distribution is presented in Fig. 4 which gives the mean diameter (D50) of approximately about 0.041 mm.

5. Procedure and employed method

Oven dried sand was filled into the ring shear box by dry deposition method following Ishihara 1989. To makes dense specimen the additional tamping method was used. Next, Co2 gas was supplied to force out the air for about an hour and then de-aired water were percolated slowly for fifteen hours to make the specimens completely

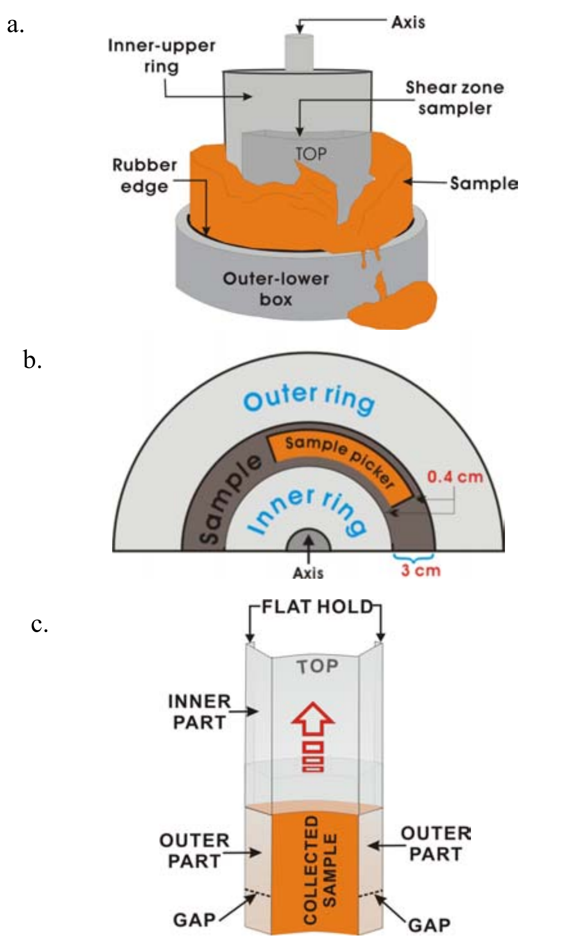


Fig. 3 Sample collecting procedure by a new shear zone sampler for DPRI Ver.5. a) the sketch to show the position of shear zone sampler in use after the upper outer ring was lifted up. b) Top viewing of half sliced of ring shear box for emphasizing the placement of shear zone sampler. c) the sketch of the situation after the sample was oven dried for 12 hours. After cooling, the inner part of the shear zone sampler was pulling out to show the developed shear zone. The marked line pointed by an arrow of 'Gap' in the Fig.. represents the location of the gap between the upper and lower boxes of ring shear

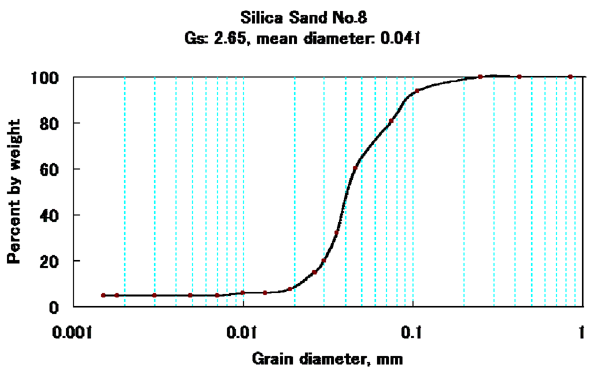


Fig. 4 Grain size distribution curve for Silica Sand No.8.

saturated. When the specimens were consolidated at 50 kPa of normal stress, the pore pressure parameter (B_D) was measured for checking the degree of saturation.

$$B_D = \frac{\Delta u}{\Delta \sigma}$$

where Δu is increment of pore pressure and Δσ is the increment of normal stress.

When the obtained B_D value is larger than 0.95 is considered as a completely saturated (Sassa, 1985) and then tests were ready to be conducted. Next, the specimens were consolidated at the initial normal stress of 180 kPa. All ring shear tests were conducted under monotonic stress-controlled condition; shear stress was increased at the loading speed of 0.098 kPa/sec and stopped at a predefined state condition based on the progression of deformation process. The situations for test A to F are shown in Fig. 5 and the list of the experiments was provided in table 1.

Since an investigation of the shear zone generation processes is the main purpose of this study, therefore four stages of deformation of the granular material under undrained monotonic stress-controlled have been selected.

The first state is that between the phase transformation and failure point. In this state one experiments were conducted (points A in the Fig. 5) with relative density of the specimen of 77.6%.

The second state, the experiments were stopped at a particular value of acceleration after the specimens has failed. Within this state three experiments were performed and stopped when the shearing speed has reached of 5 mm/sec, 16 mm/sec, and 30 mm/sec respectively. In this state each specimen has a relative density of 75.6%, 72.8%, and 73.9% respectively.

The third state is that at the steady state shearing. In this state one test was conducted with relative density of 73.9%.

For the final state, the experiment was stopped when the specimen has been sheared for about 10 m of shear displacement. In this state one test was conducted with the relative density of 78.1%.

After finishing each test, the shear zone sampler was immediately used to collect the sample of the employed specimen within the shear box just after the loading plate of the ring shear apparatus was lifted up. The collected sample then must be directly brought into the oven and let it stay for at least 12 hours in order to remove all pore water. The investigation of shear zone then performed by using a soft paint brush as a tool to clean the surface of the collected sample. The sample collecting procedure is shown in Fig. 3.

Table 1 Summary of ring shear tests on Silica Sand No.8

TEST No.	Relative density, Dr-%	Shear displacement, DL, mm	The predefined stage
A	77.6	5.5	After passing the phase transformation before failure point.
B	75.6	32	At acceleration stage when shear speed reached 5 mm/sec
C	72.4	199	At acceleration stage when shear speed reached 16 mm/sec
D	73.9	527	At acceleration stage when shear speed reached 30 mm/sec
E	73.9	1,338	In the beginning of Steady state shearing
F	78.1	10,000	At steady state shearing and large shear displacement (10 m)

After finishing the structural investigation within the shear zone, then the sample was separated into three parts i.e. the compacted oven dried (core), the adjacent zone above the core (upper) and the adjacent zone below the core (lower) parts of the collected sample, respectively (Fig. 6) in order to analyze the grains distribution of each part by hydrometer method following the standard laboratory procedure of ASTM-D421-58 (Bowels, 1978). Through out this paper to make convenience and easy to be understandable three abbreviation terms namely 'Core' for the compacted part of the collected sample; 'Upper' means the adjacent zone above the core; and 'Lower' which represent the adjacent zone below the core are used.

6. Experimental results

6.1 Shear zone

Another advantage of the new shear zone sampler is the capability to 'extract' the shear zone within the specimen after test in relative undisturbed condition. After pulling out the inner part of the shear zone sampler carefully, the investigation of the developed shear zone and its possibility of the structural growth could be performed by using soft paintbrush for cleaning the sample's surface then finally the photos were taken by a digital camera. By this method the shear zone that developed inside the collected sample is clearly exposed even in oven dried condition. More over, the collected sample could be divided into three parts i.e. the core representing the compacted (dried oven) part; the upper and lower parts of sample respectively (see Fig. 6).

6.2 Structural investigation:

The structural investigation discussed in this paper is the structure which might be developed inside the core of oven dried sample during

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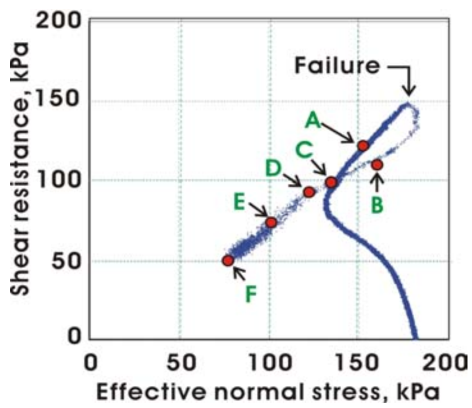

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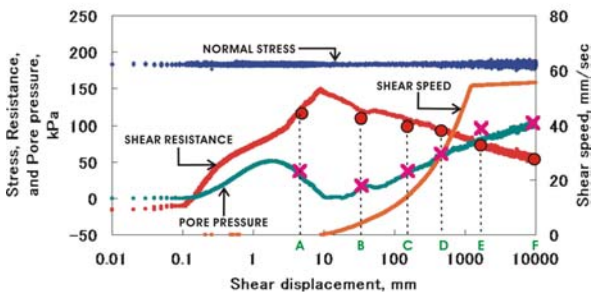


Fig. 5 Series of stress-controlled undrained monotonic tests by using ring shear apparatus under 180 kPa of initial confining pressure and 0.0981 kPa/sec of stress increment, for studying the shear zone development process on granular material. Point A—F represents the selected deformation states. a) Effective Stress Path of test F with additional end points of other tests, b) Variation of normal stress, pore pressure, shear resistance, and shear speed in relation to the shear displacement for test F (BD = 0.96, Dr = 78.1%) with additional end points of other tests (● points represents the shear resistances and ✖ points represents the pore pressures).

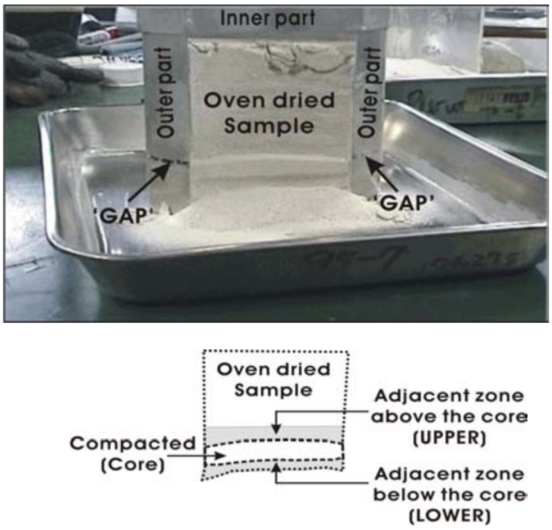


Fig. 6 The sample collected by a new shear zone sampler after oven drying for 12 hours. When the inner part of shear zone sampler was pulling out and the sample's surface was cleaned up by the soft paint brush, the compacted core of shear zone could be identified clearly. The marked line pointed by an arrow of 'Gap' in the Fig.. represents the location of the gap between the upper and lower boxes of ring shear

a.

b.

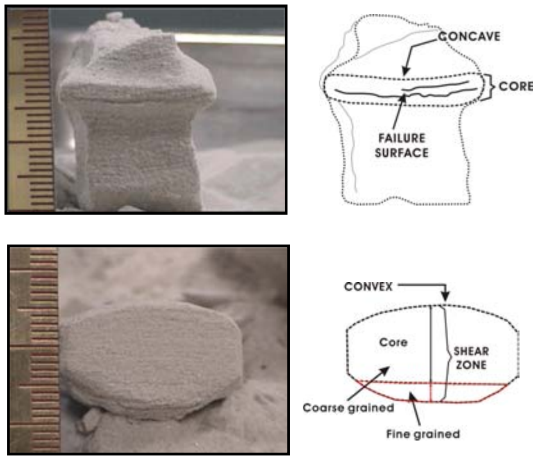


Fig. 7 Transversal cross section of the collected sample after oven dried and then sliced vertically to identify the developed shear zone. a) at acceleration stage after failure in which the shear speed was generated 16 mm/sec correspond to 5.5 mm of shear displacement. b) at the final stage i.e. after shearing for about 10 m of shear displacement. Left: the photos taken directly to the collected sample; Right: the sketch of the compacted core of shear zone and the generated structure.

deformation process. This method was selected due to the condition of the granular material itself (as a cohesionless material), means though it was predominantly by very small fraction (<0.1 mm more than 92%), but it was very difficult to collect undrained sample just as is (in wet or saturated condition) after the test without disturbing its structure. On the other hand, if the water inside the specimen be drained before collecting the sample, the developed structure inside the shear zone might also be disturbed. To avoid these difficulties therefore the oven dried sample was selected by the assumption that no structural changed when it was being dried by oven. The changing appeared by this method is only the pore water within the void of the collected sample whilts the heating effect could be neglected.

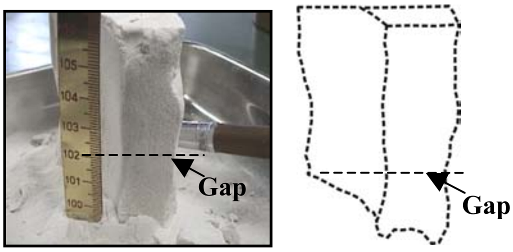
This method was employed for six experiments which represent four stages of deformation process on granular material (Silica Sand No.8). The shear zone development process which focused on the structural growth inside it will be explained below:

6.2.1 The first stage, between the phase transformation and failure point (point A in Fig. 5)

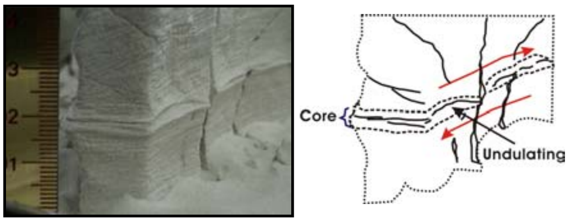
The deformed part inside the sample could not be identified by the present method; it means that the shear zone was not generated yet in the visible state (Fig. 7.a). The inter-granular relationship within this state is predominantly by rearrangement and reorientation process such as grains overriding (dilatancy) as a response to the stress increment acting along the predetermined failure plane (gap between ring boxes). Within this state the grain crushing effect at the contact faces (edges) is possibly to occur but macroscopically, this evidence can not be identified by the employed eye observation. Pore pressure generation in this state tends to decrease after passing the phase transformation point. Further, the investigation of structural growth inside the collected sample in this state revealed that no indication of compacted zone developed within the specimen and also no evidence of the accumulation of fine particles along the predetermined failure plane (marked on the shear zone sampler as shown in Fig. 6).

6.2.2 The second stage, during the acceleration after failure (point B, C and D in Fig. 5)

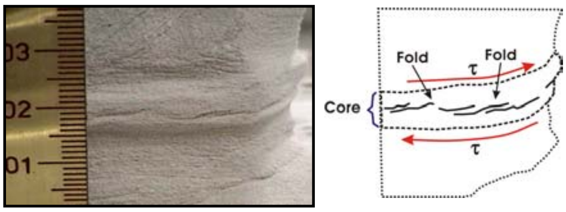
In general, within this state the fact that the upper surface of the compacted core within shear zone tend to provide the concave form as shown in Fig. 7.a according to the predetermined failure plane (gap between the ring boxes) and the thickness of the core has a tendency to increase which correspond to the generated shear speed and the distance of shear displacement. The failure surface was well developed particularly at the beginning of this state and was apparently recognized within the core.



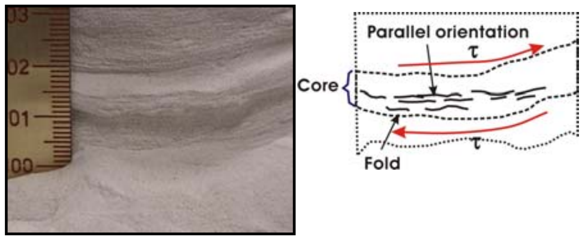
a. The collected sample when the experiment was stopped between the phase transformation and failure point (point A in Fig.. 5). No evidence of developed shear zone. The dashed line pointed by an arrow of 'Gap' in the Fig.. represents the location of the gap between the upper and lower boxes of ring shear.



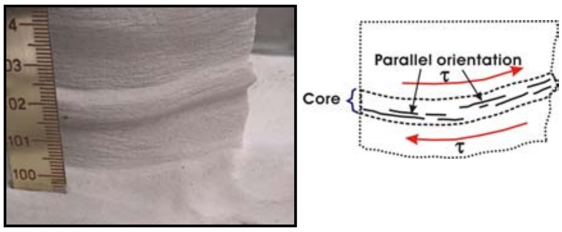
b. Asymmetrical shear zone was developed along the failure plane at acceleration state after failure in which the shear speed was generated 5 mm/sec and the shear displacement reached 5.5 mm (point B in Fig.. 5)



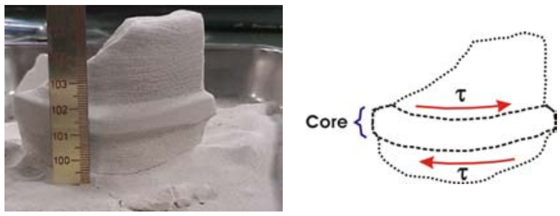
c. Fold structures within the compacted core of shear zone could be identified clearly at the acceleration state of deformation after failure in which the shear speed was generated 16 mm/sec and the shear displacement reached 32 mm (point C in Fig.. 5)



d. The tendency to become parallel orientation structure of the grains within the compacted core of shear zone at accelerating state when shear speed was generated 30 mm/sec and the shear displacement reached 199 mm (point D in Fig.. 5)



e. Relatively smooth surface with parallel orientation structure developed inside the compacted core of shear zone at the steady state in which the continuous shearing speed of 54 mm/sec was reached and the shear displacement reached 1,338 mm (point E in Fig.. 5)



f. Smooth surface of the compacted core of the shear zone at the final state when the specimen was sheared for 10,000 mm of shear displacement (point F in Fig.. 5)

Fig. 8 Evidence of the developed structure inside the compacted core of shear zone for each deformation state (point **A—F** in Fig. 5). Left: the photos which taken directly to the collected sample (the transversal cross section of a & b, and the longitudinal cross section of c—f of the collected samples); Right: the sketch of the compacted core of shear zone and the generated structure inside it

Point (B) in Fig. 5 (shear speed = 5 mm/sec)

At this state, the structure growth inside the shear zone was developed unevenly of about ± 1~3 mm (Fig. 8.b). Some parts of it show undulating and tend to grow in asymmetrical according to the predetermined failure plane (the gap between the ring boxes which marked on the shear zone sampler). This phenomenon probably because of the pore pressure within the specimen was suddenly generated partially when the specimen just failed. By another word, when the failure just occurred (the mobility has begun) the strength of the specimen particularly along the potential failure surface was developed heterogeneously.

Point (C) in Fig. 5 (shear speed = 16 mm/sec)

The core of shear zone of about 4~6 mm thick along the predetermined failure surface was developed. Inside this core, the growth of fold structure was clearly recognized (Fig. 8.c). Usually, the fold structure could be grown well on cohesive sample (ductile material) such as clay (Morgenstern and Tchalenko, 1967) or cemented material (Mandl et al., 1971). The evidence obtained by the present method probably because the specimen used in this study is mainly consists of fine particles (silty) with good uniformity coefficient (2.4) according to the grain size distribution analysis. Additionally, it was probably due to the gradual increasing of pore pressure generation without abrupt change in this test (see also Fig. 5.b. point D) which makes the discontinuity of the shear surface during deformation processes.

Point (D) in Fig. 5 (shear peed = 30 mm/sec)

At this state, the core of shear zone was created of about 6~8 mm thick (Fig. 8.d). Beside the fold structure growth inside the core, it shows the tendency of parallel orientation along the shear zone. The grain parallel orientation is common structure which developed on granular material (glass beads) under dry condition (Fukuoka, 1991) or undrained condition (Okada, 2001) by means of ring shear tests. The tendency of the grains to grow in parallel orientation obtained by the current method reflecting the response of granular material under undrained shearing at a certain value of shear speed by using ring shear apparatus.

6.2.3 The third stage, the moment the steady state appeared (point E in Fig. 5)

The thickness of the developed shear zone was about 8~10 mm thick (Fig. 8.e). Within this zone, the clear grain orientation was revealed but no fold structure inside the core could be identified. Relatively smooth surface of 'dried oven' core was exposed. This condition reflects the continuity of failure surface might be already developed by which the continuous shear speed of the lower box of ring shear has been reached. Means that the dense specimen selected in this study was already separated into two parts i.e. the relative movement part (lower), and the relative static part (upper) which separated by developed shear zone as the boundary between those parts.

6.2.4 The final stage, at the shear displacement of 10,000 mm (point F in Fig. 5)

This state represents the residual state of deformation process on granular material. The thickness of the compacted core was about 10~12 mm (Fig. 8.f). Parallel orientation is clearly developed with very smooth surface of upper 'dried-oven' core inside the shear zone. The fact that was obtained in this state when the sample was sliced vertically, the shear zone tends to developed in oval form with the concave smooth on the upper surface as shown in Fig. 7.b.

According to the facts obtained by this method, therefore the conclusion could be addressed. The development process of shear zone on granular materials is begun after failure and the thickness of shear zone tends to increase by deformation process (mobility). This process was influenced by grain crushing which correspond to the pore pressure generation during movement. From the beginning of shear zone development process to the condition in which the mobility of the specimen was generated of about 30 mm/sec the growth of uneven structure as well as fold structure (discontinuity of failure surface) could be obtained. On the other hand, at the steady state the structure was changed to parallel orientation until the end of deformation process (residual state). The degree of compaction of the core within the shear zone is also tends to increase with increasing the shear displacement

7. Grain size analysis

For more detail investigation to the shear zone development process, it should be supported by grain size analysis on the samples. Based on the ASTM D421-58 of standard laboratory test, three parts of each collected sample i.e. the compacted 'oven dried' (core), the adjacent zone above the core (upper), and the adjacent zone below the core (lower) parts respectively as discussed in the previous section, the grain size analysis were carried out. There is an exception for the sample which collected before failure (after passing the phase transformation point). As mentioned before, in this state no evidence of shear zone development process, thus the sample was divided into only two parts i.e. the adjacent zone above the 'dashed line marked on the shear zone sampler (upper) and the adjacent zone below the 'dashed line marked on the shear zone sampler (lower) parts (see Fig. 6).

Four samples representing the shear deformation process have been selected for this analysis that is one sample representing the state between the phase transformation and the failure point, one sample representing the acceleration shearing state after failure, one sample representing the steady state shearing and one sample representing the residual state that shown at the point A, C, E and F in Fig. 5 respectively, and the results will be discussed below:

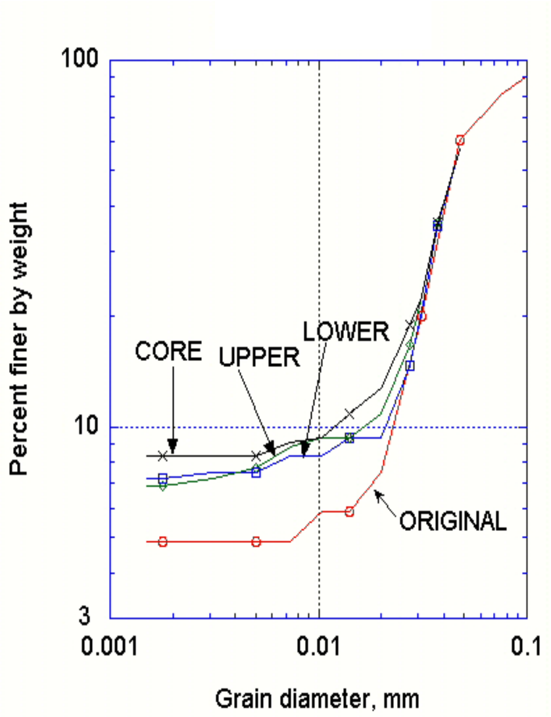


Fig. 9 Grain distributions at accelerating stage after failure (Fig.. 8.c) for each part of developed shear zone i.e. the adjacent zone above the core (upper), compacted core, and the adjacent zone below the core (lower) parts respectively.

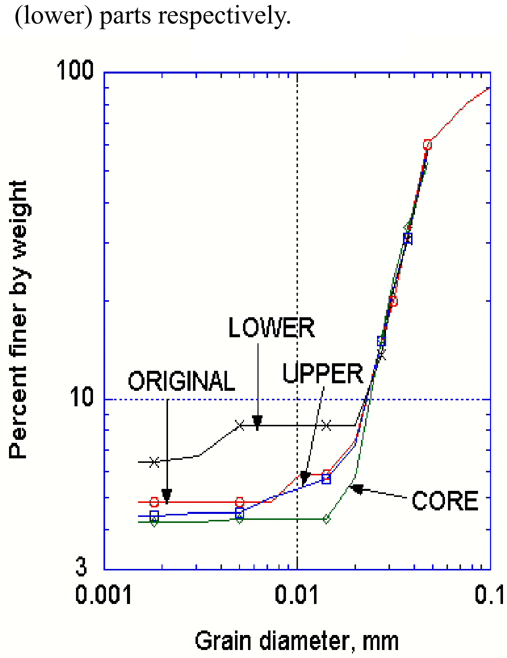


Fig. 10 Grain distributions at final stage of deformation process in which the sample was sheared up to 10 m of shear displacement (Fig.. 8.f) of each part of developed shear zone i.e. the adjacent zone above the core (upper), compacted core, and the adjacent zone below the core (lower) parts respectively.

7.1 The first stage, between the phase transformation and failure point (point A in Fig. 5)

In this state the grain distribution of the upper and lower parts are almost the same as grain distribution of the original Silica Sand No.8. The little different obtained in this state is probably because of the edge crushing when the specimen dilating as expressed by decreasing of pore pressure after passing the phase transformation or probably because of grain crushing affected by sample preparation (tamping method was used for making dense specimen) as mentioned before.

7.2 The second stage, acceleration state after failure point (point C in Fig. 5)

The shifting of grain distributions in particular at the end of the analysis for all parts (the upper, core, and lower) compared to the original Silica Sand No.8, are evidence. For the compacted core, the shifting of grain distribution is higher than the others. This condition reflecting more fine particles content in this part compared to the others. The most possible reason for this evidence is that due to the grain crushing when the specimen just failed. The other possible reason for this phenomenon, since the test is performed under undrained condition, is that during mobile (represented by generated acceleration after failure) the fine particles (including the results of grain crushing) were accumulated within the core of shear zone. By another word, the developed shear zone within this state consists of mixed grain i.e. the coarse and fine particles which distributed randomly. For the lower and upper parts of shear zone, even though they tend to shift compared to the original Silica Sand No.8, the grain distributions for those parts are almost the same. These conditions were shown in Fig. 9. Actually, during preparation of this analysis could be reported that the degree of compaction of the core was not so high (easy to be broken) but unfortunately the measurement of degree of compaction is very difficult to be performed.

7.3 The final stage, at 10,000 mm of shearing (point F in Fig. 5)

The interesting phenomenon was obtained in this state. The grain distribution of the compacted core of shear zone tends to decrease even from the original Silica Sand No.8 as shown in Fig. 10. This situation indicated that within the core part, the fine particle content is very limited compared to the other part. This phenomenon was supported by the evidence during hydrometer analysis, that after 30 minutes (7th step of hydrometer analysis procedure) the water inside the tube/jar has become clear. It means that the sedimentation process for all particles had already finished. In contrast, the grain distribution of the bottom part is shifted more than the others (Fig. 10), means that this part consists of high percentage of fine particles compared to the other parts. The possibility reason of this situation is

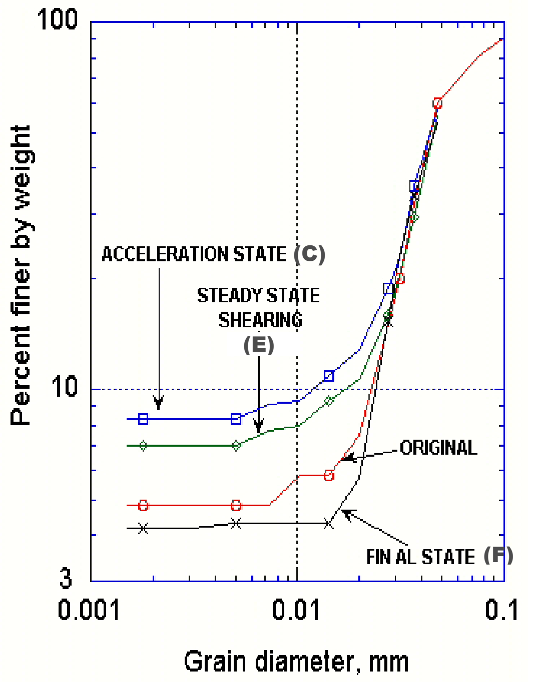


Fig. 11 Grain distributions of the compacted 'oven-dried' core of shear zone represent three states of deformation process under undrained shearing on Silica Sand No.8 (Fig.. 8.c-e-f).

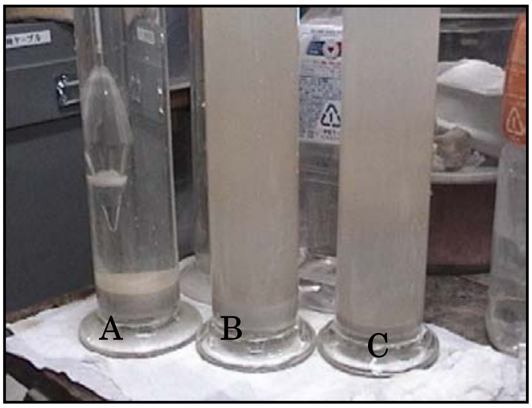


Fig. 12 Hydrometer analysis (ASTM D421-58) on each part of the collected sample after the specimen was sheared for 10 m of shear displacement. This photo was taken after 30 minutes of analysis. A, B, and C in the Fig.. represent the compacted core, the adjacent zone above the core (upper), and the adjacent zone below the core (lower) parts of shear zone, respectively.

that the lower part of shear zone is the place of accumulation of fine particle at residual state (see also Fig. 7.b). Whilst for the upper part the grain distribution is almost the same as the original.

8. Discussion and conclusion

According to the result of undrained monotonic stress-controlled tests on dense packed of Silica Sand No.8 which consolidated initially by 180 kPa of confining pressure, the shear zone development process from the beginning of deformation to the residual could be explained as follow:

From the beginning of deformation process until the state between the phase transformation and failure point based on the progress of effective stress path, macroscopically the evidence of generated shear zone could not be obtained. In this state the possibility of grain crushing in particular contact faces of grains during grains reorientation (dilation) might be occurred since the relative density is more than 70% for all tests. Unfortunately the microscopic analysis is very complicated to be conducted due to the difficulties for preparing the thin section without disturbing its structure. As the cohesionless material though it was very fine but to carry out the direct investigation to the developed structure is always problematic. Thus, for this condition macroscopically analysis is preferable. In this state, after passing the phase transformation, the pore water pressure decreases due to the increase of void ratio when the grains overriding each other (dilation) represents the grains rearrangement and reorientation process within the specimen.

The second stage of deformation process is the acceleration state post failure. In the beginning of this state the strength of the material is dropped suddenly correspond to the abruptly generation of the pore pressure and gradual increase of the shear speed (represents the mobility of specimen after failure). The generated pore pressure at the beginning of this state is shown by '**x**' in Fig. 5.b. By progressing the acceleration, the thickness of developed shear zone tends to increase correspond to the accumulation of fine particles within the shear zone. The discontinuity of failure surface which expressed by undulating and the fold structure might be developed in this state.

In the final stage of deformation process is the residual state where the parallel orientation of the grain (particularly inside the core of the shear zone) has been established and the process of separation (segregation) of the grains i.e. between the coarse and the fine particles has been reached. In this state the strength of the specimen still tends to decrease with progressing of the shear deformation until the condition in which the normal stress, resistance, and pore pressure generation become unchanged at the end of tests. In this stage, shear zone was completely generated without any increasing of the thickness (no volume changed) and also completely grain parallelism is finished, no grain crushing proceeds. This is the end of the deformation process in which usually called as steady-state (Poulos, 1981) or ultimate steady state by means of ring shear test (Wang G. and Sassa, 2002).

9. The hypothetical theory of shear zone development process in granular material

Apart from the pore water pressure generation and the grain crushing as the main role for the possibility condition of long runout landslide to occur (Sassa, 2000), the other important key which responsible to makes very low strength of granular material at the residual state is the structural development process within shear zone as shear deformation progressed.

In regards to the results of the series of experiment explained on the previous chapter, the hypothetical theory of shear zone development process by emphasizing to the structural establishment of granular materials post failure (since no evidence of developed shear zone obtained before failure, therefore the beginning stage of shear zone development process is the acceleration stage) to the residual state is proposed as shown in Fig. 13 which can be explained as follows.

When the material failed, its strength as a response to prevent the increment of stress that acting along the potential failure plane is suddenly dropped. As a consequence, the pore water pressure was generated and the mobility (acceleration) of the failed mass has begun. In this situation the shear zone was developed in asymmetrical and uneven forms (Fig. 13.a). The shear zone itself is consists of the coarse grains and its fine particles (including the results of grain crushing) which distributed randomly (mixed). Within this stage the condition inside the shear zone was expressed by its mobility which mechanically expressed by generating shear speed (acceleration) by means of ring shear apparatus. More speed generation is more fine particles content exist within shear zone affected by grain crushing and rearrangement of the originally fine particles content until the continuous shear speed has been generated.

On the other hand, at the residual state, the shear zone was separated into two parts by segregation process. The first part is the core in which the parallel orientation of the grains was established so long where the shear deformation processes still keep going. This part mainly consists of coarse grains with limited fine particles. The second part is the bottom part of the shear zone as the place for the accumulation of fine particles (Fig. 13.c). The segregation process is probably caused by the steady state shearing of the localized deformation of the specimen (shear zone) along the predetermined failure plane when the shear deformation still in progress under undrained condition.

Between those stages above (the initial post failure stage and the residual stage) there is a transitional condition namely the transition stage

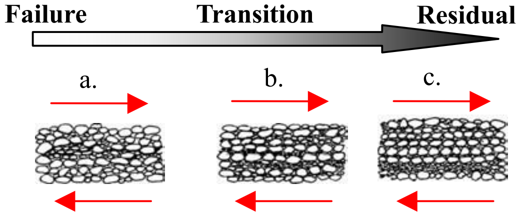


Fig. 13 The hypothetical mechanism of shear zone development process in accordance to its structural development process on granular (cohesionless) material which correspond to the shear deformation process under undrained condition by means of ring shear

(Fig. 13.b), which also represent the transitional structural development process i.e. randomly oriented to become parallel oriented of the grains along the shear zone. This situation occurred when the relative motion between the moving mass to the other has been completed. The assumption for this situation is represented by the generating of continuous shear speed by means of ring shear apparatus in which the specimen inside the rotatable box is moving relatively to the specimen inside upper box.

Based on this founding, the residual behaviour of granular material is depend on the developed structure (parallel orientation) inside the shear zone which correspond to the segregation process (separation between the coarse and fine particles during mobile) in which the fine particles as the result of the grain crushing at the acceleration state after failure and the originally contained particles of the specimen are accumulated at the bottom of the shear zone. This structure may be called as a flow structure stated by Casagrande (1971). This condition eventually reached the steady state condition (Poulos, 1981) or ultimate steady state by means of ring shear apparatus (Wang and Sassa, 2002) when the constant volume, constant effective normal stress, constant shear resistance, and constant velocity has been reached.

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リングせん断試験による非排水せん断時のすべりから流動への構造変化

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要旨

珪砂の非排水単調載荷応力制御リングせん断試験を実施し、粒状体のせん断変形過程を研究した。
次の４つの変形状態を選んで研究を行った。即ち、”phase transformation”点と破壊点の間、破壊後の加速過程、定常状態到達直後の状態、およびせん断変位 10mまでの定常状態でのせん断状態である。新しく作成したせん断ゾーンサンプラーを使って「非かく乱」サンプルを採取し調べたところ、上記各状態の進行と共にせん断ゾーンの厚さが増加する傾向にあり、せん断ゾーンは３つの部分に分割できることがわかった。この３つの部分とは即ち、コア、コアの上部、およびコアの下部である。特に最後の状態では（定常せん断中の分離作用によって）せん断ゾーン中の粗い粒子と細かい粒子が分離される傾向にあり、最終的には、「流れ構造」と一致する粒子の並行な配列構造が発達した。これは Casagrande の流れ構造の研究と一致する。この構造が粒状体の残留挙動の原因である。即ち、非排水応力制御リングせん断試験では、粒状体の変形過程において、粒子の配向、配列が大きく影響する。粒子破砕が起きた場合、残留状態において細かい粒子はせん断ゾーンの下部に蓄積する。高速長距離地すべりのメカニズムや粒状体の進行性破壊の理解においても本研究成果は非常に重要なものである。

キーワード：非排水応力制御、変形、せん断ゾーン、コア、分離、構造