2019 Rock Dynamics Summit– Aydan et al. (eds)
© 2019 Taylor & Francis Group, London, ISBN 978-0-367-34783-3

Shock test on rounded rock fragments in Suruga Bay sediments and its implications on past mega-earthquakes

I. Sakamoto
Tokai University, Dept. of Marine and Earth Science, Shizuoka, Japan

Ö. Aydan
University of the Ryukyus, Department of Civil Eng., Okinawa, Japan

ABSTRACT: The breakage of boulders/cobbles in conglomeratic deposits are reported to occur along tectonic lines. The authors have been undertaking both in-situ investigations and laboratory experiments to understand the fundamental mechanism and causes of the breakage of the boulders/cobbles. Some sampling and observations are done in the close vicinity of Horai district, which is located along the famous Median Tectonic Line of Japan. In addition, some sampling of broken boulders/cobbles was done in Seno-umi in Suruga Bay, Shizuoka by Bousei-maru investigation ship of Tokai University. A drop-weight equipment was developed to carry out experiments on the boulders/cobbles sampled from Horai district, Kusanagi and Miho district of Shizuoka City, which constitute Nihon-daira formation. The authors report the outcomes of this experimental study in relation to mega earthquakes in the past. Furthermore, some numerical studies on ideal cases were carried out in order to see the stress state causing the breakage of the boulders.

1 INTRODUCTION

It is reported the breakage of boulders/cobbles in conglomeratic deposits occur along tectonic lines (e.g. Futamura 2016). The boulders/cobbles in such environments are found to be broken either in extension, sheared or both (Fig. 1). There is no doubt that these boulders/cobbles are broken due to shock waves induced during the large seismic events. The most important aspect is how to identify the stress state and seismic shock waves causing the breakage of boulders/cobbles. The authors have been undertaking both in-situ investigations and laboratory experiments to understand the fundamental mechanism and causes of the breakage of the boulders/cobbles. Some sampling and observations are done in the close vicinity of Horai district, which is located along the famous Median Tectonic Line of Japan. In addition, some sampling of broken boulders/cobbles was done in Seno-umi in Suruga Bay, Shizuoka by Bousei-maru investigation ship of Tokai University.

Figure 1. Views of breakage of pebbles, cobbles and boulders.

The authors devised a special drop-weight equipment to carry out experiments on the boulders sampled from Horai district, Kusanagi and Miho district of Shizuoka City, which are constituted Nihon-daira formation, which is also related to the deposits in Seno-umi area in Suruga Bay. The behavior of samples under shock waves induced by the drop of cylindrical steel object from a certain height is observed. During the experiments, shock forces and accelerations were both measured simultaneously.

The maximum velocity during the impact were measured. The second author has developed some empirical relations with maximum ground velocity and earthquake magnitude (Aydan 2012). These relations may be used to infer the magnitude of the earthquakes as a function of the maximum velocity causing the breakage of the boulders/cobbles. This study may lead a new of way inference of magnitude of mega-earthquakes in the past. In addition, some finite element studies have been carried out to investigate the stress state involved in the breakage of the boulders/cobbles under different boundary conditions. The outcomes of these experimental and numerical studies are presented and their implications on the past seismicity of regions are discussed.

2 SHOCK TESTING DEVICE AND PEBBLES

2.1 *Shock Testing Device*

The authors developed a special shock testing device. The device consist of a steel cylinder with a weight of 8300 gf having a diameter of 97 mm, a load cell, an accelerometer (Fig. 2). The plastic pipe container, in which the cylinder was dropped, had an internal diameter of 100 mm and height of 500 mm. The steel cylinder was dropped from certain heights and acceleration and force were measured simultaneously using YOKOGAWA WE7000 data-acquisition system at a sampling rate of 1ms. No digital filtering was imposed on measured force and accelerometer records.

2.2 *Characteristics of Cobbles*

The size of rock fragments having different sizes are called gravel or pebble (2-64 mm), cobble (64-256 mm) or boulders (greater than 264 mm). Therefore, the testing device is limited to gravel/pebble and cobbles with a size less than 100 mm. The samples were collected at Miho-shore along Suruga Bay in which Seno-umi area exist and Kusanagi hill, which is a part of uplifted conglomeratic sea-bed deposits. The first author sampled some pebbles from Seno-umi area in Suruga Bay, Shizuoka by Bousei-maru investigation ship of Tokai University. The pebbles/cobbles in Miho and Kusanagi area are made of sandstone (Fig. 3).

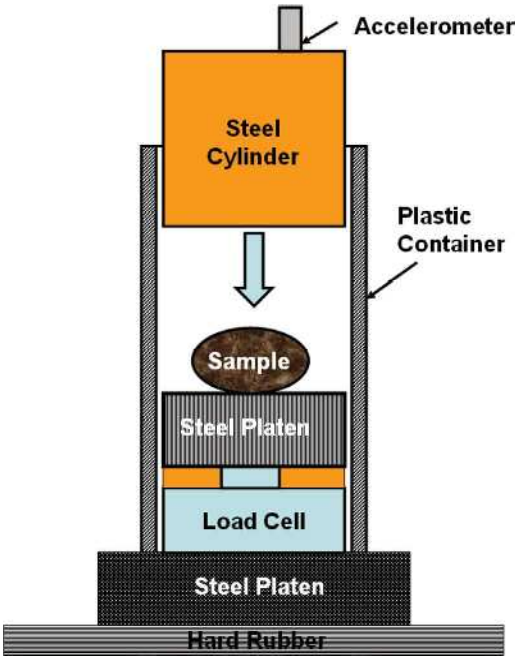

Figure 2. Schematic drawing of shock testing device.

Figure 3. Views of pebbles of Kusanagi.

The authors also visited Horai-cho district in Aichi prefecture, which is located over famous the Median Tectonic Line. In this locality, one can observe deformed and broken boulders and cobbles over a huge area. The deformed and/or broken boulders/cobbles are found in conglomeratic deposits with a fine content consists of mainly sand. Most of boulders/pebbles in this area are made of hardened shale or sandstone (Fig. 4).

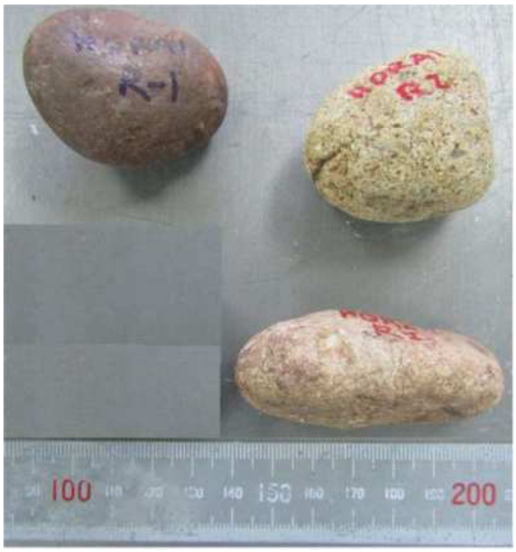

Figure 4. Views of tested pebbles of Horai-cho.

3 EXPERIMENTS AND RESULTS

3.1 *Kusanagi Pebbles/Cobbles*

The pebbles/cobbles of Kusanagi were made of sandstone. The maximum resistance depends upon the intrinsic strength of the pebble/cobble as well as its shape and drop height and fracturing state as seen in Figs. 5,6,7 and 8 and noted from Table 1. As noted from photos of the samples shown in Fig. 5, the fracturing state of samples increases as the drop height or maximum nominal velocity computed from the following formula increases:

$$V_{\max} = \sqrt{2gH_d} \tag{1}$$

where g is gravitational acceleration and H_d is drop height.

It is also interesting to note that the maximum resistance achieved before the peak acceleration occurs. Furthermore, the upward acceleration is also high, which causes the rebounding of the sample. This fact was also observed in preliminary tests with regular shapes.

Figure 5. Views of tested pebbles of Kusanagi.

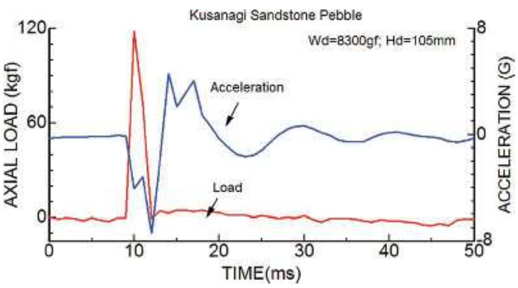

Figure 6. Force and acceleration response of Kusanagi R1 sample during the drop-weight test.

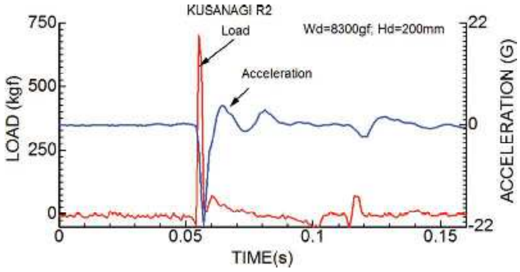

Figure 7. Force and acceleration response of Kusanagi R2 sample during the drop-weight test.

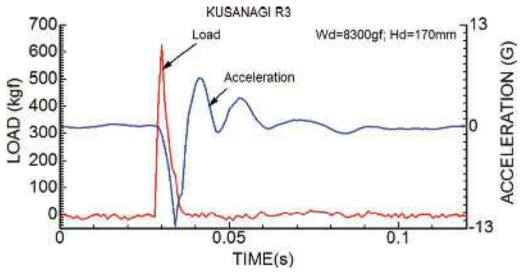

Figure 8. Force and acceleration response of Kusanagi R3 sample during the drop-weight test.

Table 1. Size and measured parameters for Kusanagi pebbles/cobbles.

Kusanagi	D(mm)	F(kgf)	|Amax| (g)	Vmax(cm/s)
R1	55	118.02	7.42	143.53
R2	65	703.04	21.72	199.09
R3	52	626.94	12.76	182.63

3.2 *Miho Pebbles*

The pebbles of Miho were made of sandstone and their resistance were quite similar as they were subjected to the maximum nominal velocity (Table 2) The fracturing state of Miho R1 sample was more destructive than that of the Miho R2 sample. The acceleration responses of the both samples are saturated.

In Miho samples, it is also interesting to note that the maximum resistance achieved before the peak acceleration occurs. Furthermore, the upward acceleration was also high, which causes the rebounding of the sample.

Table 2. Size and measured parameters for Miho pebbles.

Miho	D(mm)	F(kgf)	|Amax| (g)	Vmax(cm/s)
R1	50	103.87	11.42	177.78
R2	50	116.35	12.23	177.78

Figure 9. Views of tested pebbles of Miho after testing.

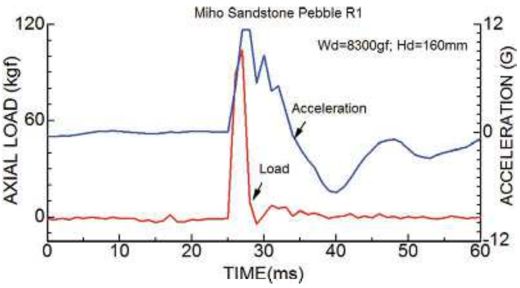

Figure 10. Force and acceleration response of Miho R1 sample during the drop-weight test.

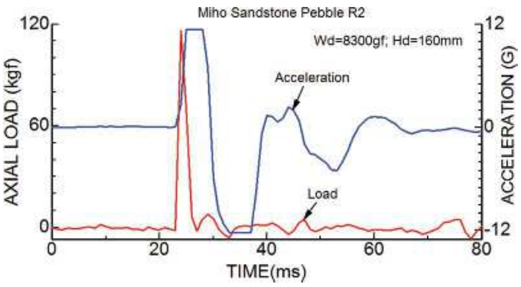

Figure 11. Force and acceleration response of Miho R2 sample during the drop-weight test.

3.3 *Horai Pebbles/Cobbles*

The pebbles/cobbles of Horai were made of hardened shale and sandstone. The Horai R1 sample, which is hardened shale did not fracture in the first test in which it was dropped from height of 135 mm. However, it was broken when the drop height was increased to 200 mm. As said previously, the maximum resistance depends upon the intrinsic strength of the pebble/cobble as well as its shape and drop height and fracturing state as seen in Figs. 12,13,14 and 15 and noted from Table 3. As noted from photos of the samples shown in Fig. 13, the fracturing state of samples R1 and R2 involved a single rupture surface while Horai R3 sample had several rupture surfaces. As also noted in previous experiments, the acceleration response is not symmetric with respect to time axis.

Figure 12. Views of tested pebbles of Horai after testing.

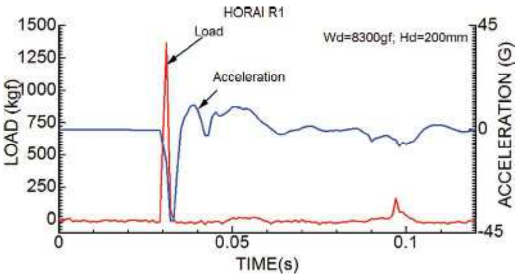

Figure 13. Force and acceleration response of Horai R1 sample during the drop-weight test.

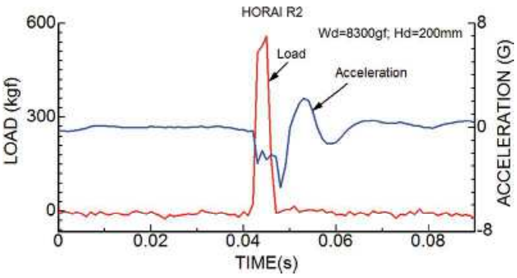

Figure 14. Force and acceleration response of Horai R2 sample during the drop-weight test.

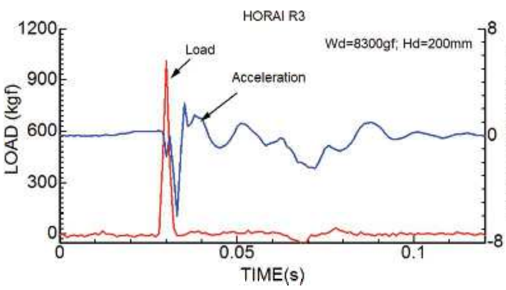

Figure 15. Force and acceleration response of Horai R3 sample during the drop-weight test.

Table 3. Size and measured parameters for Horai pebbles/cobbles.

Horai	D (mm)	F (kgf)	|Amax| (g)	Vmax (cm/s)	Comment
R1-1	50	95.54	12.22	162.75	Not broken
R1-2	50	1367.16	39.88	199.09	Broken
R2	50	558.63	7.65	199.09	Broken
R3	68	1015.21	5.99	199.09	Broken

4 NUMERICAL STUDIES ON ROUNDED ROCK FRAGMENTS EMBEDDED IN SOFTER MATRIX UNDER VARIOUS LOADING CONDITIONS

The site observations indicated that rounded rock fragments were embedded in matrices having softer materials. A series of preliminary numerical analyses were carried out to see the deformation and stress state in the rounded rock fragments and surrounding matrix under static condition assuming that material behaviour was elastic. Material properties used in numerical analyses are given in Table 4 while Fig. 16 shows the displacement and force boundary conditions. The domain was subjected to four force conditions, nameli CASE 1: shearing; CASE 2: normal loading and CASE 3: normal and shearing loading and CASE 4 shearing under non-uniform normal loading. The shear and normal load intensities are given in Table 5. CASE 4 was considered in order to take into account the possibility of non-uniform normal load distribution at the top boundary in reality.

Figs. 17 to 20 shows the maximum shear stress distributions in the analyzed domain. Except the lower boundary due to fixed boundary condition, the numerical analyses are not uniform within the domain and the rock fragments act like stress attraction area within the domain. In other words, the stresses are much higher in the harder rock fragments. This situation would be more amplified as the stiffness between the inclusions (rock fragments) and matrix become larger. Figs. 21 to 23 show the principal stress vectors under shearing, combined shearing and normal loading and non-uniform normal loading. In this figure it is again noted that the stresses on hard inclusions are higher. The stress

Table 4. Material properties used in numerical analyses

Material	Elastic Modulus (GPa)	Poisson's ratio
Rock Fragment	10	0.25
Matrix	1	0.30

Table 5. Loading Conditions

CASE No	Shear Traction (MPa)	Normal Traction (MPa)
1	1.0	0.0
2	0.0	1.0
3	1.0	1.0
4	0.0	1.0,5.0 (over cobble)

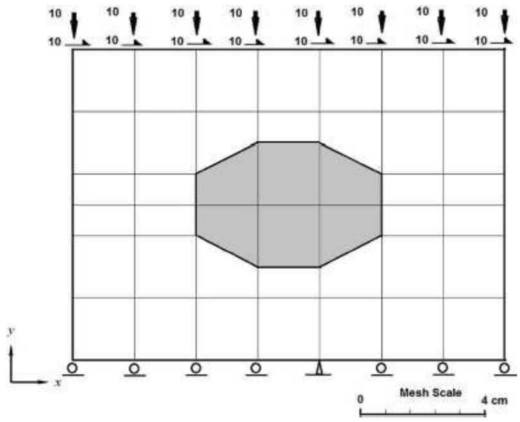

Figure 16. Boundary conditions (CASE 3)

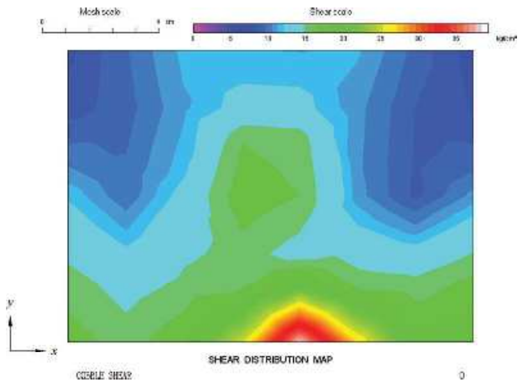

Figure 17. Max. shear stress distribution (CASE 1)

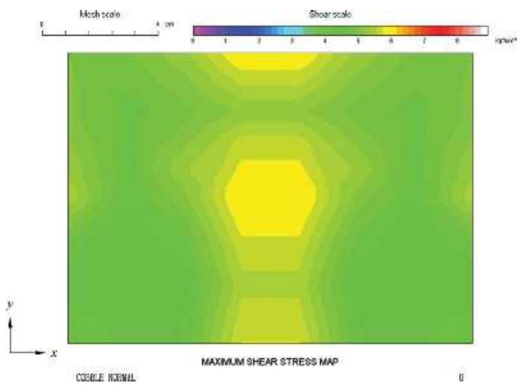

Figure 18. Max. shear stress distribution (CASE 2)

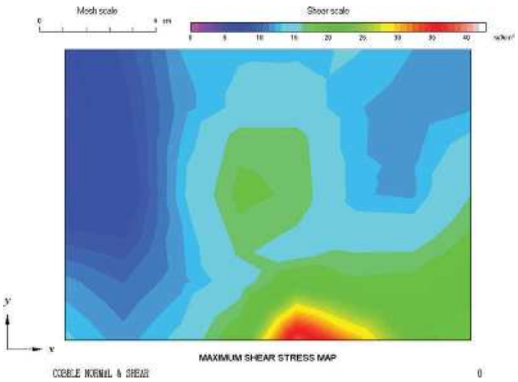

Figure 19. Max. shear stress distribution (CASE 3)

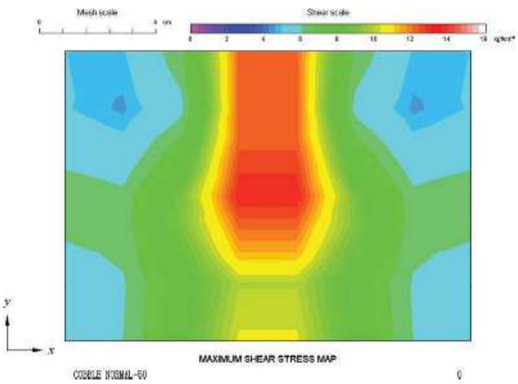

Figure 20. Max. shear stress distribution (CASE 4)

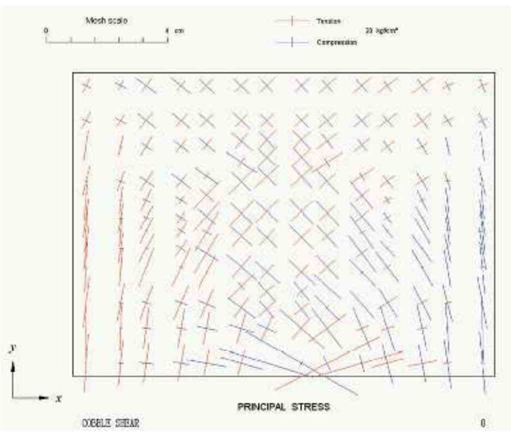

Figure 21. Distribution of principal stresses(CASE 1)

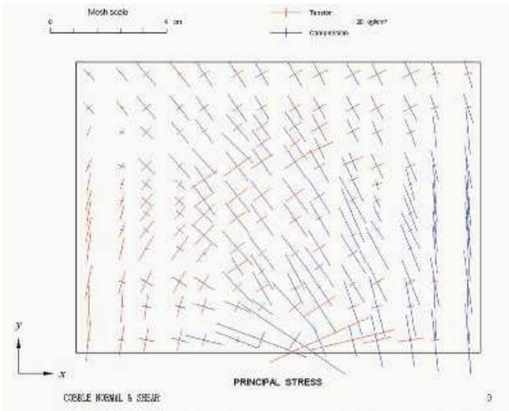

Figure 22. Distribution of principal stresses(CASE 3)

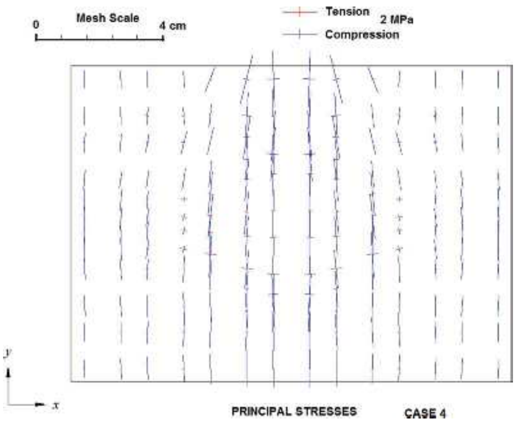

Figure 23. Distribution of principal stresses(CASE 4)

distributions for CASE 1 and CASE 3 indicates that if stress state is enough to rupture the inclusions, tension cracks will occur at an angle of 45 degrees or more with respect to the shearing direction.

Under high normal loads, tensile stresses develop in inclusions perpendicular to applied direction of normal loads as seen in Fig. 23. As the intensity of normal load increases the tensile stresses also increases. In other words, if inclusion ruptures in extension, there will be fractures through the rock fragments parallel to the direction of loading, which may also indicate the maximum stress direction.

5 INFERENCE OF EARTHQUAKE MAGNITUDE

Aydan (2012) proposed some empirical relations between magnitude and seismic parameters of the earthquakes. The equations developed by Aydan may be applied to the source area of the earthquake by assuming that the rupture of the rock fragments occur. Thus, the moment magnitude of the earthquake can be estimated from the following relation for the maximum velocity in the source area as

$$M_w = 1.16 * \ln(6.8 * V_{\max}) \tag{2}$$

If the values, which are obtained from the maximum velocity to fracture the rock fragments in experiments on samples from the Suruga Bay deposits, are used in Eq. (2), one would infer the moment magnitude of earthquakes as 7.99, 8.23, 8.26 and 8.37 in Suruga Bay. The moment magnitude of earthquakes in Suruga Bay is known to be ranging between 7.9 and 8.4 since 1400. Thus the estimations from the broken rounded rock fragments are in accordance with the past earthquakes in the region.

6 CONCLUSIONS

The causes of breakage of rounded rock fragments in conglomeratic deposits are experimentally studied through a specially developed experimental device, which is equipped with a load cell and an accelerometer. When the maximum nominal velocity is sufficient to cause the fracture of the rounded rock fragments, it may correspond to the maximum velocity in the source area of the earthquake. With this assumption, it is shown that it is possible to estimate the magnitude of the earthquake from Eq. (2) together with the maximum nominal velocity sufficient enough to cause the rupture of the rounded rock fragments. In additions, the stress state due to imposed deformation conditions imposed during the earthquake is analyzed using numerical methods and it is shown that the fracture of rounded fragments are possible in extension, shearing or both.

REFERENCES

Aydan, Ö. (2012): Ground motions and deformations associated with earthquake faulting and their effects on the safety of engineering structures. Encyclopedia of Sustainability Science and Technology, Springer, R. Meyers (Ed.), 3233–3253.

Futamura, K. 2016. Sinistral brittle shearing in the Fudesute Conglomerate of Lower Miocene Suzuka Group, Kameyama City, Central Japan (in Japanese) (Chikyu Kagaku), 70, 95–108.