Introduction
It is instinctively expected that giant earthquakes occur around spring tide because the tidal stress variation around spring tide is the largest. Fujii et al. (2013), however found that there were dangerous lunar phases for each subduction zones in which giant earthquakes concentrated and the lunar phases did not have to be around spring tides. Another phenomenon triggering our interest is that most buildings broken during giant earthquake while many rock cliffs keep stable during giant earthquakes but collapse during creep when the stress is lower. These phenomena seem to suggest that rock do not have to fail during larger stress.

To clarify the mechanism behind these phenomena, series of uniaxial compression tests were carried out on Kimachi sandstone and Shikotsu welded tuff. The experimental results were discussed based on strain rate-dependent rock strength and fatigue damage.

Experiments on Kimachi sandstone
Kimachi sandstone was sampled at Shimane prefecture, Japan, and is a relatively well-sorted clastic rock with a typical grain size range of 0.4-1.0 mm. The 30 mm \( \phi \times 60 \) mm cylindrical specimens were made with a parallelism of 20 μm at both ends through drilling, cutting and grinding. Then specimens were dried in an 80°C oven for 48 hours and kept at room temperature at least 5 days before the test. Specimens were alternatively subjected to constant loading rate of \( 10^{-5} \text{ s}^{-1} \) for 50 s and five waves of triangular loading, reverse triangular loading, small amplitude triangular loading or large amplitude triangular loading (Fig. 1a-d) for 50 s until failure.

A sudden stress drop was considered to be rock failure. The explanation for failure timing including “constant loading” and “cyclic loading” is shown in Figure 2 and the example of rock failing during constant loading or cyclic loading are shown in Figure 3. Experimental results were summarized based on rock failure timing in Table 1.
Figure 2. Explanation of “constant loading” and “cyclic loading”.

Table 1. Summary of the results ($p$: the probability of the random null hypothesis to have $m$ or more specimens failing during cyclic loading).

<table>
<thead>
<tr>
<th>Loading pattern</th>
<th>Constant</th>
<th>Cyclic</th>
<th>$p$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triangular</td>
<td>10</td>
<td>8</td>
<td>76</td>
</tr>
<tr>
<td>Reverse</td>
<td>10</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Large</td>
<td>0</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Small</td>
<td>2</td>
<td>3</td>
<td>50</td>
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Hypothesis testing was used to verify whether the rock failing timing is random. The probability $p$ of the random null hypothesis which assumes that rock failure timing is random for the case where $m$ or more rock specimens fail during cyclic loading was calculated using the following equation.

$$p = \sum_{j=0}^{n} \left( h \left(1-h\right)^{n-j} \times C_{j} \right)$$  \hspace{1cm} (1)

where $n$ is the total number of specimens, $h$ is the probability that a rock specimen fails during cyclic loading (0.5), $C_j$ is the number of combination for the case where $j$ specimens are selected from $n$ specimens. Usually the random null hypothesis is rejected when $p$ is smaller than 5%.

Results of rock failure timing and the probability $p$ are shown in Table 1. For the triangular loading test, reverse triangular loading test and small amplitude triangular loading test, many rock specimens failed during constant rate loading. The probability is much larger than 5% and the rock failure timing is statistically considered to be random. While in the large amplitude triangular loading test ($n = 5$ and $m = 5$), all rocks failed during larger strain (Fig. 4). The probability $p$ was smaller than 5% and the random null hypothesis was rejected. It can be statistically concluded that the specimens failed during larger strain under larger triangular loading.

Figure 3. Example of rocks failing during constant loading (a) and cyclic loading (b) in triangular loading test.

Figure 4. Explanation of “larger strain” and “smaller strain”.

**Explanation of Kimachi sandstone**

According to Sano (1981), logarithm of rock strength $\sigma_{\text{max}}$ increases linearly with logarithm of strain rate $\dot{\varepsilon}$ (Fig. 5) and their relationship can be expressed as equation (2).

$$\sigma_{\text{max}} = Ae^{\frac{1}{\varepsilon}}$$  \hspace{1cm} (2)

where $A$ is a constant and $n$ is the stress corrosion index. The stress corrosion index $n$ and constant $A$ was evaluated as 63 and 44.8 MPa for Kimachi sandstone through the one specimen method proposed by Hashiba et al (2006). Substituting $n$, $\dot{\varepsilon}$ and $A$ into equation (2), theoretical strength increase due to the cyclic loading can be calculated.
To theoretically explain the results of rock failure timing, stress increase (Fig. 6) was measured and UCS increase was calculated based on Sano’s equation that how much the strength will increases when strain rate increases from constant loading \((1\times10^{-5} \text{ s}^{-1})\) to cyclic loading \((11\times10^{-5} \text{ s}^{-1})\) for triangular loading test, \(101\times10^{-5} \text{ s}^{-1}\) for large amplitude triangular loading test and \(2\times10^{-5} \text{ s}^{-1}\) for small amplitude triangular loading test).

For triangular and small amplitude triangular loading tests, stress increase is similar to theoretical strength increase (Fig. 7). Rock failures were therefore random, which is analogous with the past research that static stress increases of less than 0.01 MPa can only trigger very few seismicity (Hardebeck et al., 1998). For the large amplitude triangular loading tests, stress increase is much larger than the theoretical strength increase. It is natural that all specimens failed during larger strain.

**Experiments on Shikotsu welded tuff**

The Shikotsu welded tuff mainly consists of plagioclase, hypersthene, augite, hornblende, and transparent glass having a felt-like structure with amoebic form in the matrix (Doi, 1963). Similar experiments including triangular loading test, reverse triangular loading test and new loading pattern high frequency triangular loading test (Fig. 8) were performed on Shikotsu welded tuff to obtain a more general conclusion.

**Figure 5.** Relationship between rock strength \(\sigma_{\text{max}}\) and strain rate \(\dot{\varepsilon}\).

**Figure 6.** Stress increase \(\Delta\sigma_i\) and stress amplitude \(\Delta\sigma_A\).

**Figure 7.** Theoretical UCS and average actual stress due to the larger strain rate at the loading part of the cyclic loading. S: small amplitude triangular loading test, T: triangular loading test, R: reverse triangular loading test.

**Figure 8.** High frequency triangular loading

The results of rock failure timing on Shikotsu welded tuff are summarized in Table 2. For triangular loading test, rock failure timing is random and more rocks failed during constant loading than during cyclic loading, which is similar with the result of Kimachi sandstone. For reverse triangular loading test, the probability of rock failure is smaller than 5% and the random null hypothesis was rejected and it can be statistically said that Shikotsu welded tuff tends to fail during cyclic loading under reverse triangular loading test. For high frequency triangular loading
test, although the null hypothesis cannot be rejected but more rocks failed during cyclic loading. This results might show the influence of stress wave frequency on rock failure timing.

Table 2. Summary of the results (p: the probability of the random null hypothesis to have m or more specimens failing during cyclic loading).

<table>
<thead>
<tr>
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<tr>
<td>Triangular</td>
<td>5</td>
<td>3</td>
<td>86</td>
</tr>
<tr>
<td>Reverse</td>
<td>1</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>High frequency</td>
<td>3</td>
<td>8</td>
<td>11</td>
</tr>
</tbody>
</table>

Explanation of Shikotsu welded tuff
For triangular loading test, stress increase (Fig. 9) is slightly larger than UCS increase. Rock failure timing was therefore random.

For reverse triangular loading test, stress increase and stress amplitude of cyclic loading is larger than that of triangular loading test. It’s reasonable that more rock failed during cyclic loading. The fatigue effect during cyclic loading seems to be more serious than Kimachi sandstone. This could probably be due to the absence of clay minerals in rock which could absorb energy by plastic deformation and prevent fatigue cracking.

For high frequency triangular loading test, the stress increase is smaller than the UCS increase due to short loading duration and theoretically most rock should fail during constant loading. However, comparing to the result of triangular loading test, more rocks failed during cyclic loading in high frequency triangular loading test and rock failure timing is statistically random. This would imply that the fatigue effect during cyclic loading seems to be severer than Kimachi sandstone.

Conclusions
Experimental results suggest that rock specimens did not have to fail under larger strain when the stress amplitude was smaller than a certain value, even if the cyclic loading is with high frequency as revealed by the result of high frequency triangular loading test. The results coincide with the phenomena that rocks do not always fail under spring tide or larger Earth tidal stress and many rock cliffs collapse during creep not giant earthquakes. The mechanism behind the experimental results was explained based on strain rate-dependent rock strength and fatigue damage.

Tests on other types of rock will be required to generate a more general conclusions. Triaxial tests for saturated specimens would be suggested as a more realistic experimental condition. I would be greatly appreciated if our finding could contribute to deeper understanding of mechanisms behind giant earthquake or rock cliff failures.

REFERENCES


