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Evaluation of elastic region of the surrounding bedrock using the cyclic unconfined compression test of rocks

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ABSTRACT: The seismic response analysis is typically carried out to evaluate the seismic resistance of the civil engineering structure including the surrounding bedrock related to nuclear power facilities. The bedrock is conservatively assumed to be a linear material in the seismic response analysis. It is confirmed that the stress ratios (= stress/failure strength) occurring in the bedrock are within 0.5 from result of the seismic response analysis. Therefore, the multi-stage cyclic compression test of the rock was performed in order to confirm whether the bedrock is generally elastic against the stress ratio. As a result, it was confirmed that the stress-strain relation of the rock specimens were almost linear until the loading stage just before the failure and the elastic wave velocities of the rocks were not generally nearly decreased. Therefore, they has been shown it is reasonable evaluation method to assume the bedrock as a linear material.

1 INTRODUCTION

In Japan, the seismic response analysis is typically carried out to evaluate the seismic resistance of civil engineering structure including the surrounding bedrock related to nuclear power facilities. Stress-strain relation of bedrock is conservatively assumed to be a liner elastic material in the seismic response analysis and Young's modulus are calculated from elastic wave velocity, because the stress ratio (= stress/failure strength = reciprocal of local safety factor) is basically used as an evaluation index in the seismic response analysis.

On the other hand, a condition of bedrock is not clear while the stress is increasing in case that bedrock is received by cyclic loading like seismic wave. Stress-strain relation of bedrock is assumed to keep elastic condition on small stress range, but become a plastic state little by little as the stress increases. Regarding the surrounding bedrock of civil engineering structure in Takahama Nuclear Power Plant (operated by Kansai Electric Power Co., Ltd), it is confirmed that the stress ratios occurring in the bedrock is smaller than about 0.5 from the result of seismic response analysis. The bedrock consists of rock and discontinuity and it is assumed that the rocks bear external shear force like seismic wave. If the rock keeps elastic condition while stress ratios are within 0.5, it is appropriated that the bedrock is assumed to be a liner material in the seismic response analysis. Therefore, elastic region of the surrounding bedrock shall be indirectly evaluated by tests which uses the rocks as specimens in this paper.

Thus, the multi-stage cyclic compression test (hereinafter called "compression test") and measurement of the ultrasonic wave velocity of rock (hereinafter called "measurement of ultrasonic") were carried out in order to confirm that the rock keeps elastic condition at stress ratios within 0.5, after the rock is loaded by cyclic compression force.

2 OUTLINE OF TEST

Compression test of rocks were carried out referencing Japanese Geotechnical Society standard (JGS2561: Method for multi-stage cyclic undrained triaxial test on rocks). The test was carried out under the condition that confining pressure was zero (which means the uniaxial compression test) to conservatively evaluate elastic region of the rocks.

Measurement of ultrasonic was carried out according to Japanese Geotechnical Society standard (JGS2110: Method for laboratory measurement of ultrasonic wave velocity of rock by pulse test). The frequency of ultrasonic element of test machine was set to 200Hz in P wave and 100Hz in S wave, referencing the unconfined compression strength test results that had been carried out before than this time.

2.1 *Specimens of test*

The rock types used as test specimens are the rhyolite, andesite and rhyolite tuff, which are main rock types in the site of Takahama Nuclear Power Plant. However, the distribution range of rhyolite tuff is slight compared to that of rhyolite and andesite. It is assumed that the unconfined compression strength of rhyolite and andesite is about 100MPa and that of rhyolite tuff is about 40MPa from the test results carried out before than this time.

The rock specimens using the boring core samples are shaped 5cm in diameter and 10cm in height according to JGS2561. The moisture contents of the rock specimens are 0.91% in rhyolite, 1.25% in andesite and 1.28% in rhyolite tuff on average. Strain gauges are put in an axial direction and in a circumferential direction on both sides position at the center of the specimen height. The length of strain gauges at axial direction is 20mm or 60mm and at circumferential direction is 20mm or 30mm according to the grain size included in the specimens.

2.2 *Method of test*

The procedure of the test is shown in the Figure 1.

At first, to confirm the initial status of the rock specimen, the ultrasonic wave velocity of the rock specimen was measured before the STEP1 of compression test. In STEP1, compression test

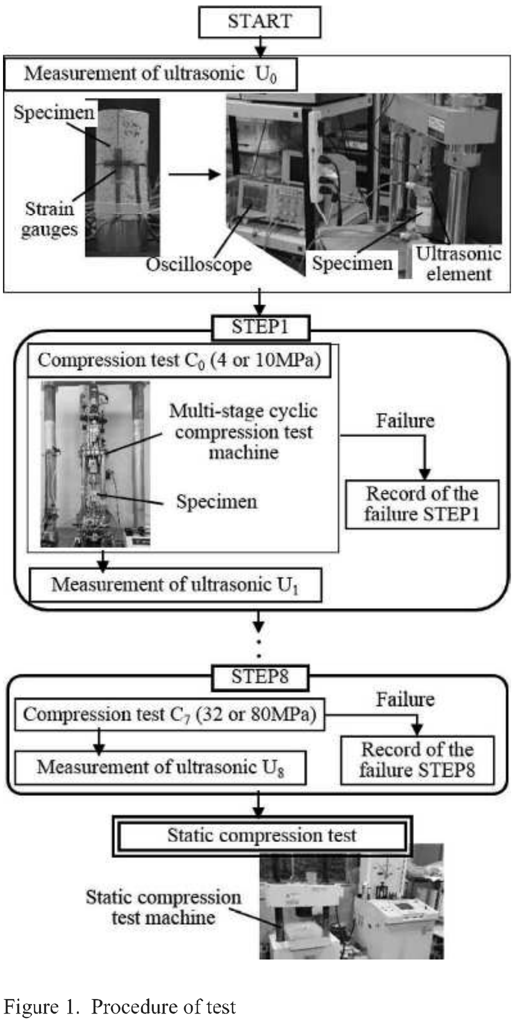

Figure 1. Procedure of test

and measurement of ultrasonic were conducted. Compression test was conducted with 10% load of the unconfined compression strength (10MPa : rhyolite and andesite, 4MPa : rhyolite tuff). Then, the ultrasonic wave velocity of the rock is measured. The cyclic loading was increased 10% for every STEP (the cyclic loading in STEP2 is 20%, the cyclic loading in STEP3 is 30%). 10 cycles was given in one step of compression test. If the rock specimen doesn't reach to the failure by the end of STEP8, the static compression test was conducted to confirm the compression strength. However, in case that the rock specimen reaches to the failure before the end of STEP8, cyclic loading at the time of the failure was recorded as the compression strength. The frequency of cyclic loading of compression test was basically 1Hz according to JGS2561. However, compression test was also implemented with 2Hz frequency, because it is confirmed that one of the basic ground motions in Takahama site responds to around 2Hz of the seismic frequency band. Stress-strain relation in every cyclic compression load was recorded and equivalent Young's modulus was calculated from 10th wave at every STEP of compression test.

3 THE RESULT OF TEST

The initial status including elastic wave velocity of the rock specimens before compression test is shown in Table 1. Initial density (ρ_0), P wave velocity (hereinafter called V_p) and S wave velocity (hereinafter called V_s) from measurement of the ultrasonic wave velocity (U_0), dynamic Young's modulus (E_d) calculated from V_p and V_s, equivalent Young's modulus (E_{eq}) obtained by STEP1 of compression test (C_0), the step of the failure, failure strength, failure strain and frequency of the cyclic loading are shown in this table. In case that the rock specimen reaches to the failure by static compression test, "static" is written at the column of "step of the failure" in Table 1. Rhyolite, andesite and rhyolite tuff are written Rh, An and Rh(T) in Table 1.

3.1 *The result of measurement of ultrasonic wave velocity*

The results of V_p and V_s obtained from measurement of ultrasonic are shown in Figures 2 and 3, respectively. The result of V_p and V_s of every STEP is normalized by initial ultrasonic wave velocity shown in Table 1 (hereinafter called "normalized V_p, V_s"). Normalized V_p, V_s are plotted on the vertical axis in these Figures. The values of the uniaxial stress is normalized by the failure strength are plotted on the horizontal axis. The uniaxial stress is recorded in 10th cycles of every STEP.

When the value of axial stress/failure strength was 0.5, normalized V_p decreased about 0% to 5%

Table 1. Initial status before compression test and result of test

	V_p (m/s)	V_s (m/s)	E_d (MPa)	E_{eq} (MPa)	ρ_0 (g/cm^3)	Step of failure	Failure strength (MPa)	Failure strain	Loading Frequency
Rh1	3,811	2,481	33,654	20,354	2.415	static	124.99	0.554	1
Rh2	3,914	2,539	35,681	20,791	2.435	static	122.08	0.499	1
Rh3	3,266	2,172	24,999	14,130	2.401	7	69.54	0.459	1
Rh4	3,373	2,187	25,876	15,477	2.379	8	79.79	0.483	1
Rh5	3,454	2,219	27,178	15,178	2.402	5	50.05	0.321	1
Rh6	3,215	2,058	23,138	14,862	2.369	5	46.75	0.335	1
Rh7	3,833	2,511	34,188	19,799	2.412	static	104.36	0.458	2
Rh8	3,377	2,190	26,033	16,043	2.388	static	88.10	0.503	2
Rh9	3,498	2,216	27,599	13,271	2.411	5	38.83	0.406	2
An1	4,900	2,850	51,432	51,554	2.545	static	110.79	0.234	1
An2	4,859	2,702	47,472	41,033	2.548	static	83.34	0.232	1
An3	3,067	1,960	21,298	12,341	2.400	6	58.02	0.344	1
An4	4,534	2,634	42,826	36,426	2.479	static	92.27	0.236	2
An5	3,748	2,359	32,272	23,951	2.474	8	77.66	0.331	2
Rh(T)1	3,062	2,026	21,078	12,514	2.311	static	37.71	0.316	1
Rh(T)2	2,919	2,050	19,711	11,934	2.315	static	61.44	0.571	1
Rh(T)3	2,789	1,926	18,109	9,905	2.338	static	81.31	0.778	2
Rh(T)4	2,772	2,035	17,844	10,506	2.352	static	58.30	0.592	2

※About Rh(T)4, it's carried out 11steps and static test

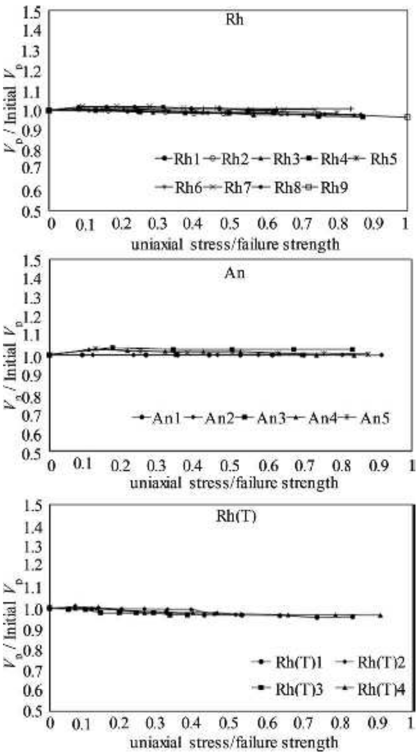

Figure 2. Result of V_p

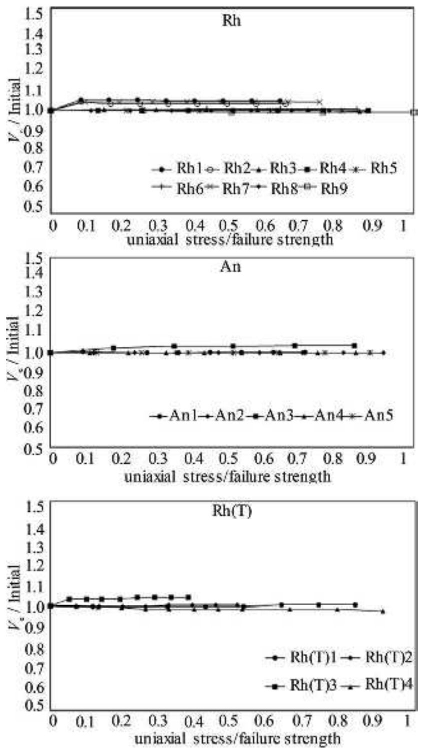

Figure 3. Result of V_s

and normalized V_s basically did not change from initial value. Furthermore, both normalized V_p and normalized V_s decreased within 5% just before the failure. It was confirmed that there were almost no differences of the test results by rock types and by cyclic wave frequency. On the other hand, there were some specimens where the elastic velocity increase from initial value. These facts are considered in *3.3 the result of stress-strain relation.*

The average values for each 0.1 step of axial stress/failure strength from all test results are shown in Table 2. The sample standard deviations from Figures 2 and 3 were 0.143 for normalized V_p and 0.045 for normalized V_s. From above, it was confirmed that though the elastic wave velocity was falling as the cyclic compression load increases, the falling rate of the elastic wave velocity was included within the margin of variability.

3.2 *The result of compression test*

Equivalent Young's modulus from the result of compression test is shown in Figure 4. Calculating methods of Young's modulus are written below for each case. In case of calculating from the cyclic loading test, Young's modulus are calculated from the slope of line that connects the peak load coordinate and the coordinate where shear stress is 0, which is average value between the start coordinate before the compression load and the end coordinate after the compression load, to consider residual strain. In case of calculating from the static compression test, Young's modulus is calculated from the slope of line that connects point of the coordinate before the compression load and the coordinate of the failure. Equivalent Young's modulus from test results are divided by initial equivalent Young's modulus shown in Table 1, and the value of equivalent Young's modulus is normalized such that initial value is 1.0. Normalized equivalent Young's modulus is plotted on the vertical axis in this Figure. The value of the uniaxial stress divided by the failure strength is plotted on the horizontal axis. The uniaxial stress is recorded in 10th cycles of every STEP.

Equivalent Young's modulus of rhyolite slightly increased as the cyclic compression load increases. And that of andesite barely decreased. On the other hand, that of rhyolite tuff decreased at first, but conversely increased from the middle as cyclic load increases. After all, it was confirmed that the range of fluctuation is within 20% when the value of axial stress/failure strength is 0.5, and the fluctuation barely changes just before the failure. It was also confirmed that there were almost no differences of test results by rock types and by cyclic compression wave frequency. However, the elastic wave velocity of An3 increased from initial value. These facts are considered in *3.3 the result of stress-strain relation.*

The average values for each 0.1 step of uniaxial stress/failure strength from all test results are shown in Table 3. The sample standard deviation from Figure 4 was 0.153. From above, it was confirmed that though the elastic wave velocity was falling as the cyclic compression load increases, the falling rate of the elastic wave velocity was included within the margin of variability.

Table 2. Average of V_p, and V_s

Stress ratios	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
V_p	1.00	1.00	0.95	0.91	1.00	0.99	0.94	0.96	0.98	–
V_s	1.02	1.01	1.01	1.01	1.01	1.01	0.98	0.97	0.99	–

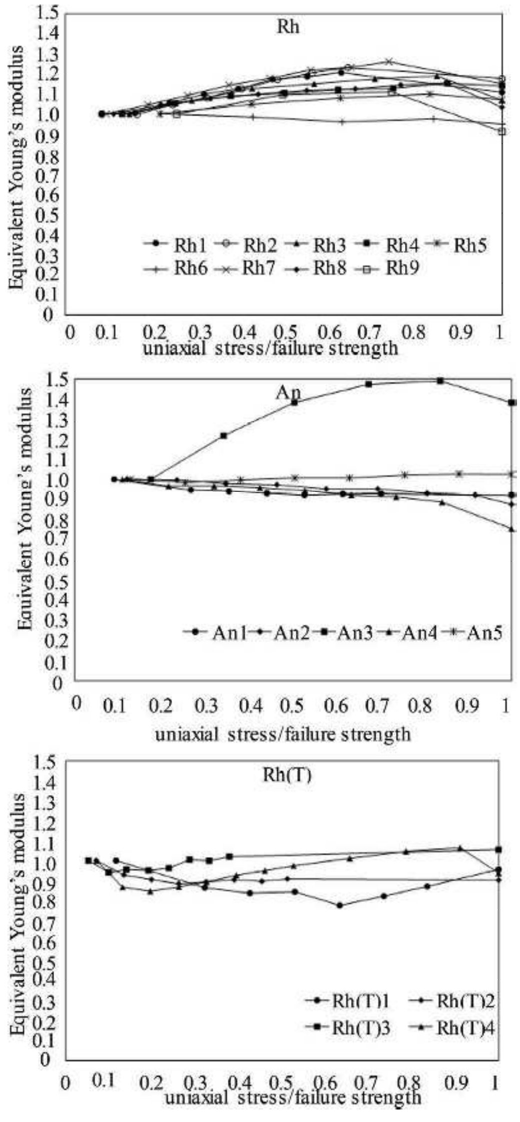

Figure 4. Equivalent Young's modulus

Table 3.Average of equivalent Young's modulus

Stress ratios									
0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Equivalent Young's modulus									
0.98	0.99	1.01	1.03	1.05	1.06	1.07	1.08	1.03	1.01

3.3 *The result of stress-strain relation*

In this chapter, the facts that normalized V_p, normalized V_s and equivalent Young's modulus from the result of stress-strain relation increased as the cyclic load increases are considered.

Stress-strain relation of Rh2, in which the falling rate of normalized V_s and equivalent Young's modulus are relatively large compared to other specimens, is shown in Figure 5. Stress-strain relation of Rh2 has the feature of convex curve below. As one of the reasons why stress-strain curve is convex below, it is considered that rock specimens had invisible weakened parts or potential cracks (hereinafter called "potential cracks"). So it is assumed that potential cracks are compressing as the cyclic load increases, and the stiffness of the rock specimens increase. It is assumed that the equivalent Young's modulus increased as test STEP progresses due to the same reason.

Stress-strain relation curve at 10th cyclic wave load from STEP1 to STEP8 are shown in Figure 6. Though the slopes are almost same in the range of small uniaxial stress from STEP1 to STEP8, the slope in the range of small uniaxial stress is gentler than that of large axial stress for each STEP. From above, it is assumed that equivalent Young's modulus increases in case that the uniaxial stress exceeds a certain value because potential cracks disappear due to compression at the axial stress. The slope of all STEPs in the range of small uniaxial stress is almost same, so it is considered that the damage of the rock specimens is extremely small.

The stress-strain relation curves of Rh1, Rh3, Rh4, Rh5 and Rh6 are similar to that of Rh2. Especially, the stress-strain relation curve of Rh1 is almost the same as that of Rh2. However, the stress-strain curves of Rh3, Rh4, Rh5 and Rh6 (hereinafter called "Rh3 to Rh6") are slightly more bent under than those of Rh2. It is assumed that the rock specimens of Rh3 to Rh6 have more potential cracks than that of Rh2, judging from the fact that the initial values of E_d and E_{eq} of Rh3 to Rh6 are smaller than those of Rh2. As a reference, the stress-strain relation of Rh3 is shown in Figure 7.

The results of An1 and An3 shall be considered. About An1, the degree of fluctuation of equivalent Young's modulus is very small. On the other hand, the degree of fluctuation of equivalent Young's modulus of An3 is very large. Stress-strain relation of An1 and An3 are shown in Figures 8 and 9. It is considered that An1 has almost no potential cracks because the shape of stress-strain relation is almost straight line, and furthermore, the falling rate of equivalent Young's modulus does not exceed over about 5% from the initial load to the failure load. On the other hand, stress-strain curve of An3 is convex below like that of Rh2. So it is assumed that potential cracks are distributed in the rock specimen of An3, different from An1. Therefore, it is consid-

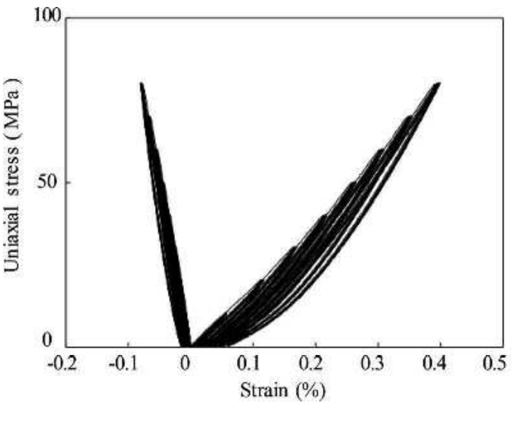

Figure 5. Stress-strain relation of Rh2

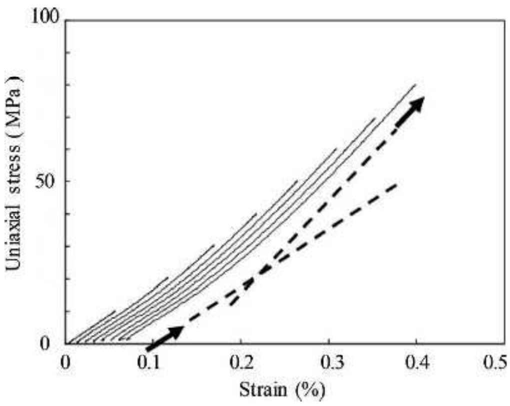

Figure 6. 10th wave (STEP1-8) stress-strain relation

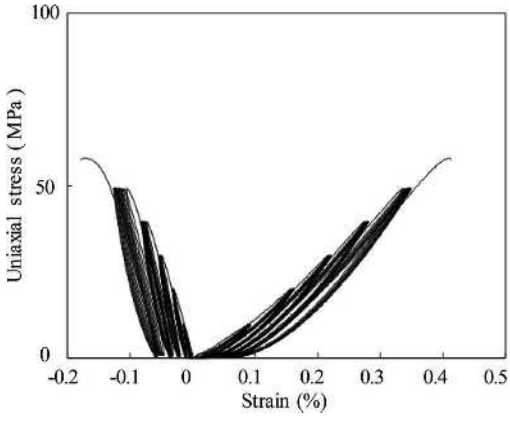

Figure 7. Stress-strain relation of Rh3

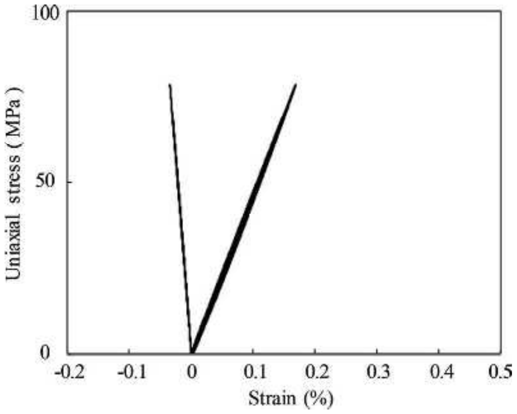

Figure 8. Result of An1 stress-strain relation

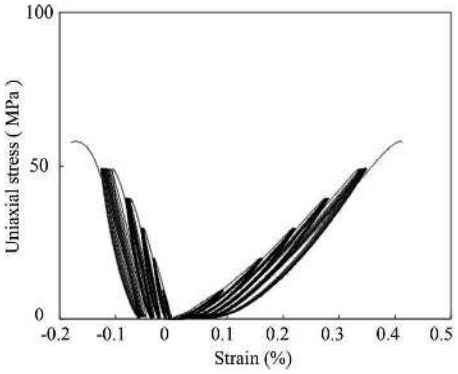

Figure 9. Result of An3 stress-strain relation

ered that the difference of fluctuation of equivalent Young's modulus between An1 and An3 results from the amount of the potential cracks in the rocks. This reasoning is consistent with the fact that the initial values of E_d, E_{eq} and rock density of An3 shown in Table 1 were definitely small compared with that of An1.

In order to confirm above reasoning, the results of the specimens where the initial values of E_d, E_{eq} and rock density are similar, are compared. Stress-strain relation of Rh2 and Rh7 are shown in Figures 5 and 10. It is confirmed that the shapes of stress-strain relation of Rh2 is similar with that of Rh7 which has similar initial value of E_d, E_{eq} and rock density of Rh2, although the frequency of cyclic load of Rh1 is different from that of Rh7.

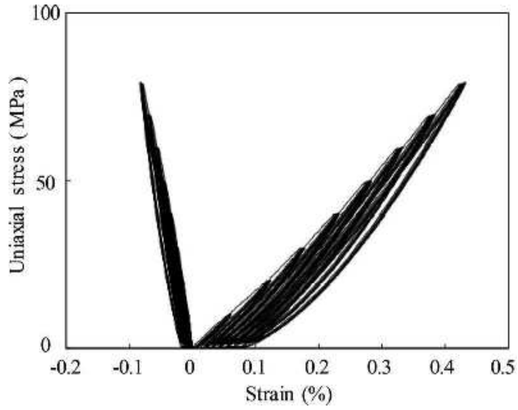

Figure 10. Result of Rh7 stress-strain relation

4 CONCLUSION

The elastic wave velocities of the rocks were hardly falling in spite of the cyclic loads increasing, it is assumed that the rocks generally keep elastic just before the failure. On the other hand, the range of fluctuation of equivalent Young's modulus was within 20% for every STEP in cyclic loading test, although equivalent Young's modulus of the rock specimens change as the cyclic load increases due to the potential cracks. It was assumed that the damage of the rock specimens was very slight and the rocks kept generally elastic, because the rigidity of the rock specimens such as E_d or E_{eq} did not fall from initial measurement in spite of increasing of cyclic load.

Therefore, it was confirmed that the bedrock keeps generally elastic in the stress status just before the failure over the stress ratio 0.5, and it was a reasonable condition in the evaluation method to assume the bedrock as a linear elastic material in the site of Takahama site. Moreover, it was confirmed that the seismic resistance of civil engineering structure including the surrounding bedrock could be conservatively evaluated by using dynamic Young's modulus calculated from elastic wave velocity.

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