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# EVALUATION OF ACCURACY OF SEISMIC RESPONSE ANALYSIS OF GROUND USING RADAR CHART

Y. Ohya[(1)], A. Nozu[(2)], N. Yoshida[(3)], E. Kohama[(4)], T. Sugano[(5)]

[(1)] *Senior Researcher, Port and Airport Research Institute, ooya-y@pari.go.jp*
[(2)] *Director of Division, Port and Airport Research Institute, nozu@pari.go.jp*
[(3)] *Professor, Tohoku Gakuin University, yoshidan@tjcc.tohoku-gakuin.ac.jp*
[(4)] *Head of Group, Port and Airport Research Institute, kohama-e83ab@pari.go.jp*
[(5)] *Senior Adviser, Coastal Development Institute of Technology, t_sugano@cdit.or.jp*

## *Abstract*

Use of a radar chart is proposed as a tool for evaluating the accuracy of the seismic response analysis of a ground, as the result of the seismic response analysis is used in variety ways and important feature is different to each other. Seven indices, i.e., peak ground acceleration, peak ground velocity, spectral intensity, instrumental seismic intensity, power spectral intensity, predominant period, and maximum shear strain, are chosen as earthquake motion indices. Two vertical array records, the Kushiro port during the 1993 Kushiro-oki earthquake and Port Island during the 1995 Kobe earthquake, are analyzed by the equivalent linear, total stress truly nonlinear and effective stress analyses and compared. Effective stress analysis showed good agreement with observed records. Parametric study by means of scaled input earthquake motion indicates that difference of analytical methods are very small when maximum shear strain is less than 0.1 %, but it increases as the maximum shear strain increases. The radar chart was very convenient to evaluate the accuracy of the result of analysis because error can be seen from variety of stand point in one glance.

*Keywords: seismic response analysis of ground, liquefaction, radar chart, earthquake motion index*

## 1. Introduction

Concerning the seismic response analysis of a ground, it is important to choose an analytical method according to the structural classification and magnitude of earthquake motion. Three typical methods, i.e., equivalent linear, total stress truly nonlinear and effective stress analyses, are well known and have been used in the practice. Ishihara [1] proposed the compatible-strain ranges relating to the accuracy of these analytical methods. Therefore, applicability of equivalent linear, total stress truly nonlinear and effective stress analyses is discussed based on this reference in many research studies even now. Clear criteria of applicability of the analytical method, however, have not been specified yet.

In the past research, applicability of the seismic response analysis was mostly evaluated by ambiguous criteria such as the resemblance of acceleration waveform. Even if quantified, the maximum acceleration was merely used for evaluation. But it seems that it is problematic with discussion of calculation accuracy with these ambiguous evaluations because the seismic response analysis is used for various purposes. Furthermore, it has been important to grasp applicability limit and error of the analytical methods because the design earthquake motion has been increased significantly after the year 1995 and the response of ground in a large-strain region has not been an unusual result.

This study proposes a method for evaluating accuracy of the seismic response analysis of a ground using earthquake motion indices. Earthquake motion indices have hitherto been used to explain characteristics of earthquake motion and earthquake damage. The essence of this study is to use these indices for evaluating the accuracy of the seismic response analysis and a radar chart which consists of several earthquake motion indices is used in order to present earthquake motion indices visually and multilaterally, and evaluate the analytical accuracy impartially.

In this paper, we discuss validation of applicability limit of equivalent linear and total stress truly nonlinear analyses using the radar chart for two earthquake records whose shear strain in ground exceeded 1%. The cases this paper targets are the vertical array at the Kushiro port where influence of dilatancy in the acceleration waveform was shown during the 1993 Kushiro-oki earthquake and the vertical array at Port Island where the amplitude of the acceleration time history decreased due to liquefaction of the reclaimed soil during the 1995 Hyogoken-nambu earthquake.

It is assumed that it is difficult to apply the equivalent linear and total stress truly nonlinear analyses in the large-strain region in where influence of dilatancy of materials like sand cannot be ignored. This paper validated the degree to which the strain levels of equivalent linear and total stress truly nonlinear analyses could secure reproducibility to the effective stress analysis using a radar chart with seven evaluation indices of analytical accuracy.

## 2. Validation method

### 2.1 Indices for evaluating analytical accuracy

This study assumes that the seismic response analysis of ground is used for consideration of the earthquake damage in design. Then the following seven earthquake motion indices which are used for evaluation of the earthquake damage are selected for consideration of analytical accuracy in this study. Alphanumeric characters in the parenthesis indicate indices and units of measurement; symbols are used by the radar chart later on. For details of indices, for instance, see Yoshida [2]. All indices except maximum shear strain are calculated from the time history of acceleration at the ground surface.

1) Peak ground acceleration (*PGA*, cm/s$^2$): The maximum of the absolute acceleration at the ground surface.
2) Spectral intensity (*SI*, cm/s): The spectral intensity (the SI value hereafter) was proposed by Housner [3]. In this study, following the Japanese engineering practice, velocity response spectrum with 20% damping ratio $S_{v,20}$ is divided by the integral time interval (2.4 s) in calculating the SI value so that unit of the SI value becomes cm/s (Katayama [4]). Then in this study, the latter expression is used as

$$SI = \frac{1}{2.4}\int_{0.1}^{2.5} S_{v,20}\,dt \tag{1}$$

3) Acceleration for the instrumental seismic intensity ($a_0$, cm/s$^2$): The instrumental seismic intensity $I_{JMA}$ (Japan Meteorological Agency [5]) is calculated as

$$I_{JMA} = 2\log a_0 + 0.94 \tag{2}$$

where $a_0$ denotes the reference acceleration. It is defined as sum of the time in which absolute acceleration exceeds $a_0$ becomes exactly 0.3 s. The instrumental seismic intensity $I_{JMA}$ is a logarithmic indication of the acceleration, so it is a favorable index by the meaning that it can be expressed as a numerical value for sensually grasping the motion of a very small to a very large earthquake. But, for example, even if the acceleration doubles, a change in the instrumental seismic intensity is merely 0.6 and the sensitivity is low as the index used for evaluation of accuracy. Then $a_0$ is regarded as the sensitivity as much as the acceleration and $a_0$ which is an index equivalent to the instrumental seismic intensity is used instead of the instrumental seismic intensity in this study. Because $a_0$ has not been named, the name "acceleration for the instrumental seismic intensity" is used here.

4) Power spectral intensity (*PSI*, cm/s$^{0.5}$): The power spectral intensity of velocity (the PSI value hereafter) is defined as a square root of square integral value of velocity waveform and written as

$$PSI = \sqrt{\int v^2 dt} \tag{3}$$

where $v$ denotes the absolute velocity at the ground surface and the integral is made in whole duration. It is considered as an index which indicates good correlation with degree of earthquake damage to port structures (Nozu and Iai [6]).

5) Peak ground velocity (*PGV*, cm/s): The maximum of the absolute velocity obtained by integrating the acceleration at the ground surface in the frequency domain. Then the 0.1 Hz high-pass filter is applied for the integration.

6) Predominant frequency of transfer function ($F_p$, Hz): The predominant frequency is a peak frequency in the long-period side of the transfer function defined as the ratio of the acceleration at the base to the acceleration at the ground surface. This frequency is equal to the natural frequency in a primary mode of ground and shows the seismic characteristic of the entire ground model. When more than one peak appears in the transfer function, the predominant frequency is selected while comparing with transfer functions obtained by analytical cases with different input accelerations in this study. Namely, the predominant frequency is not always a simple maximum amplification ratio of the transfer function in the long-period side.

7) Maximum shear strain (*STR*, -): The maximum shear strain occurs in the ground. When the maximum shear strains obtained by different analytical methods are compared, sometimes depth which indicates the maximum value differs because of the deformation mode of the ground differences.

## 2.2 Radar charts

Radar charts consisting of seven earthquake motion indices are used to evaluate analytical accuracy in this study. By using such a radar chart, it is possible to show graphically analytical accuracy among multiple indices. Two kinds of radar charts are used in this study. The first radar chart uses the ratio of the analytical result of each analytical method to an observed record. This radar chart consists of six indices because there were no observed records of the maximum shear strain (*STR*). The second radar chart uses the ratio of the analytical result of the total stress truly nonlinear analysis or equivalent linear analysis to the effective stress analysis.

Incidentally, what criteria should be selected for comparison depends on the comparative purpose. For instance, when discussing reproducibility of actual phenomena, observed records should be selected as criteria. When discussing differences among the analytical methods, i.e. comparison of expression of stress-strain model, the truly nonlinear analysis with a step-by-step time integration in the time domain should be selected as criteria.

### 2.3 Analytical methods

The analytical methods subjected to consideration are equivalent linear, total stress truly nonlinear and effective stress analyses. In this study, the total stress truly nonlinear analysis is defined as an analytical method where the dilatancy of soil is not taken into account.

A computer program, FLIP (Iai et al. [7]), is used for both effective stress and total stress truly nonlinear anlyses. A constitutive model which combined the excess porewater pressure rise model with the multi-spring model is used for the effective stress analysis. Then excess porewater pressure rise model is handled as invalidity for the total stress truly nonlinear analysis because it is defined as an analytical method which does not consider dilatancy of soil. Consequently, a difference between the total stress truly nonlinear analysis and effective stress analysis is whether or not the change of mechanical characteristic is taken into account due to the fluctuation of effective stress as a result of the generation of excess porewater pressures, and there is no difference in the non-liquefiable layer where excess porewater pressure does not rise.

Equivalent linear analysis based on the multiple-reflection theory and SHAKE is one of the most popular computer programs derived from this theory. In this study, the DYNEQ (Yoshida [8]) computer program which has various functions the same as SHAKE is used and the Hardin-Drnevich model is used for the stress-strain model of the ground.

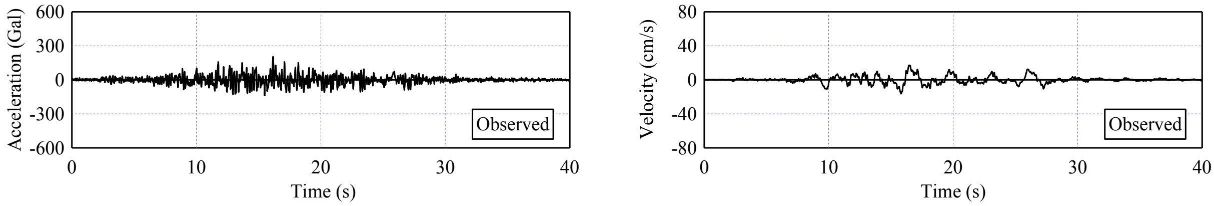
Shear wave velocities and reference strains for each depth is specified based on mean effective confining stress which is calculated by self-weight analysis before both total stress truly nonlinear and effective stress analyses. The next-earthquake response analysis takes intial stresses and strain histories calculated by self-weight analysis over and starts. But such anisotropy due to initial stress and strain histories cannot be considered in the equivalent linear analysis.

## 3. Validation based on record during the 1993 Kushiro-oki earthquake

### 3.1 Site and method of analysis

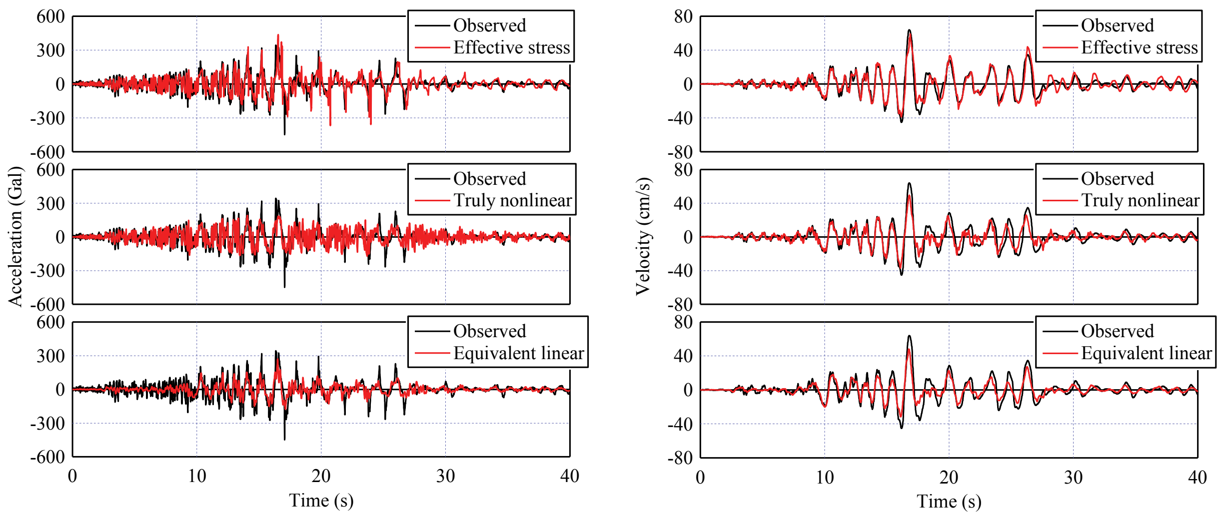
The vertical array at the Kushiro port during the 1993 Kushiro-oki earthquake is used for investigation. Acceleration records were obtained at two depths, the ground surface and G.L. -77 m at the observation site at the Kushiro port. The acceleration record at the ground surface showed the characteristic waveform which becomes the predominant waveform in cycles of 1.5 seconds overlapped by a spike at each peak. A case study of the effective stress analysis which considered dilatancy in dense sand layers and the ground condition at the observation site was conducted with FLIP (Iai et al. [9]). The FLIP analysis showed reproducibility of the acceleration record of a spike-shaped waveform and indicated that the record at the ground surface was influenced by nonlinear behavior of the surface layer. Then this case study shows the advantages of the effective stress analysis in large-strain region because shear strain in the ground exceeded 1%. In this study, the slightly correcting ground model is used in order to further improve the reproducibility of the velocity waveform, for details see Nozu [10].

The acceleration record at the base for the analyses and the velocity waveform obtained by integrating the acceleration are shown in Fig. 1. The subject of analyses is conducted for the NS component which is the larger component among the two horizontal components. Figure 2 shows acceleration and velocity time histories at the ground surface obtained by the effective stress, total stress truly nonlinear and equivalent linear analyses compared with observed records, respectively. The effective stress analysis could reproduce the velocity time history and acceleration time history, which shows a spike-shaped waveform and long-period component after the maximum acceleration amplitude, more accurately than the total stress truly nonlinear and equivalent linear analyses. In this study, 10 cases of analyses from 0.1 times to 1.0 time at an interval of 0.1 times based on the amplitude of the acceleration records at the base, are conducted and the results of each analysis are evaluated with the radar chart.




a) Acceleration b) Velocity

Fig. 1 – Earthquake record at the Kushiro port during the 1993 Kushiro-oki earthquake (G.L. -77 m)




a) Acceleration b) Velocity

Fig. 2 – Comparison of analytical and observed time histories (Ground surface)
(The 1993 Kushiro-oki earthquake)

### 3.2 Accuracy evaluation by means of radar chart

Radar charts which show the ratio of the analytical results to the observed record of each index are shown in Fig. 3. All indices except for the predominant frequency of transfer function ($F_p$) show that a result of the effective stress analysis reproduces the observed values more accurately than those of the total stress truly nonlinear and equivalent linear analyses judging from shape of the radar charts. Then the radar charts indicate that the results of both the total stress truly nonlinear and equivalent linear analyses underestimated observed values among most of the evaluation indices, and especially the maximum accelerations of analytical results are about half of the observed value. A spike-shaped waveform in the acceleration time history by influence of dilatancy of soil appears and the maximum acceleration is recorded at a spike-shaped waveform. It is not possible to reproduce a spike-shaped waveform by the total stress truly nonlinear and equivalent linear analyses which do not consider dilatancy of soil, so the maximum acceleration becomes quite smaller than the observed value. On the other hand, the effective stress which can consider dilatancy of soil reproduces the spike-shaped waveform and the maximum acceleration calculated by this analysis nearly equals the observed value.

Because the results of effective stress analysis show high reproducibility of the observed values judging from this radar chat, these results are regarded as correct values that correspond to each evaluation index. Then accuracy of total stress truly nonlinear and equivalent linear analyses is expressed such that these become higher accuracy according as these results closer to the results of the effective stress analysis in the following analytical cases.

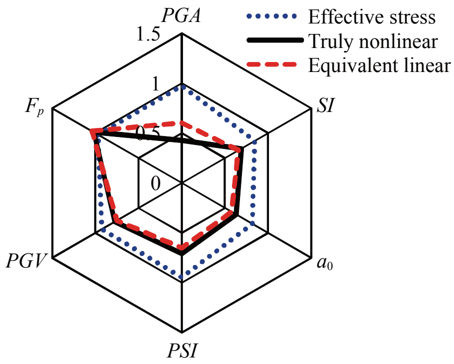



Fig. 3 – Comparison of radar chart (Analytical result/Observed value)
(The 1993 Kushiro-oki earthquake)

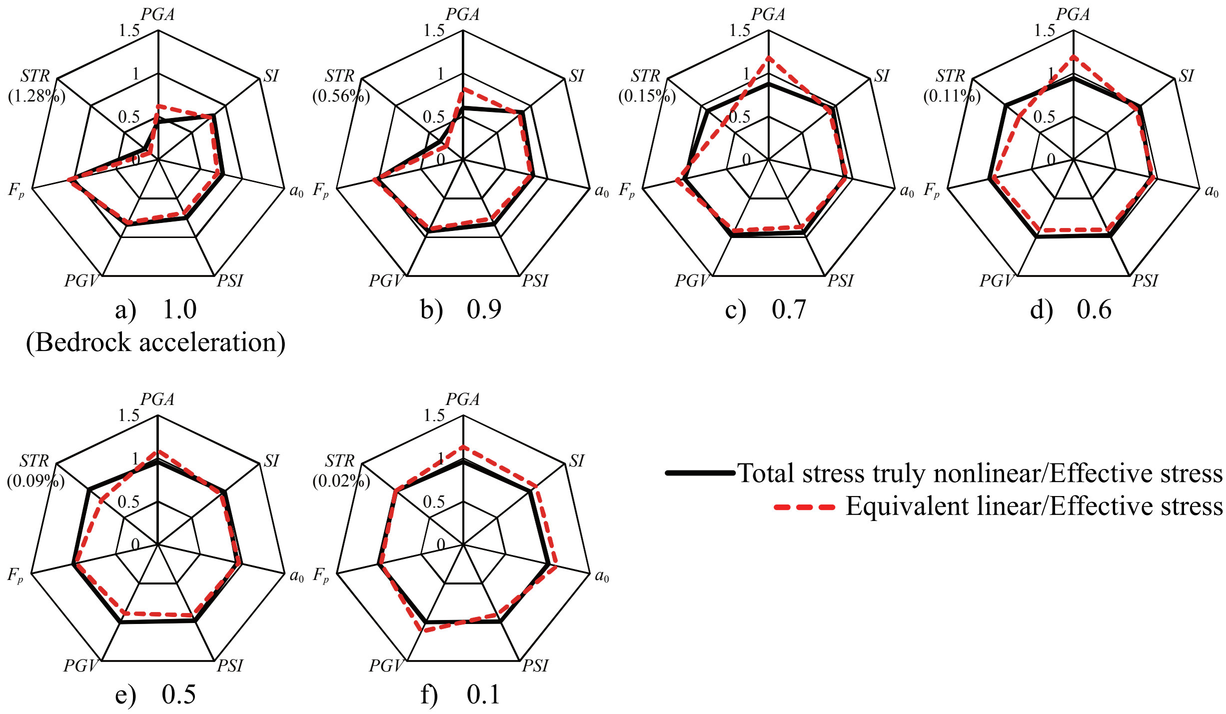
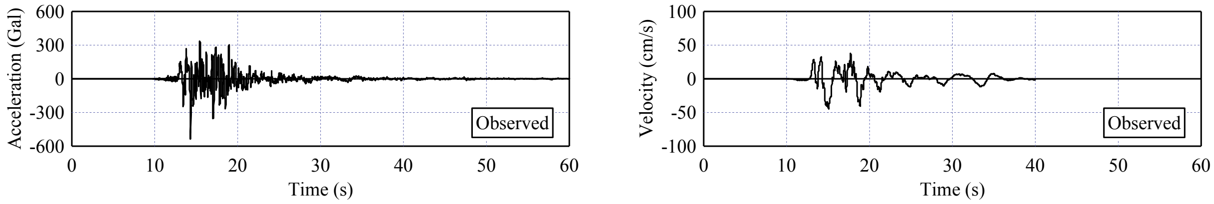


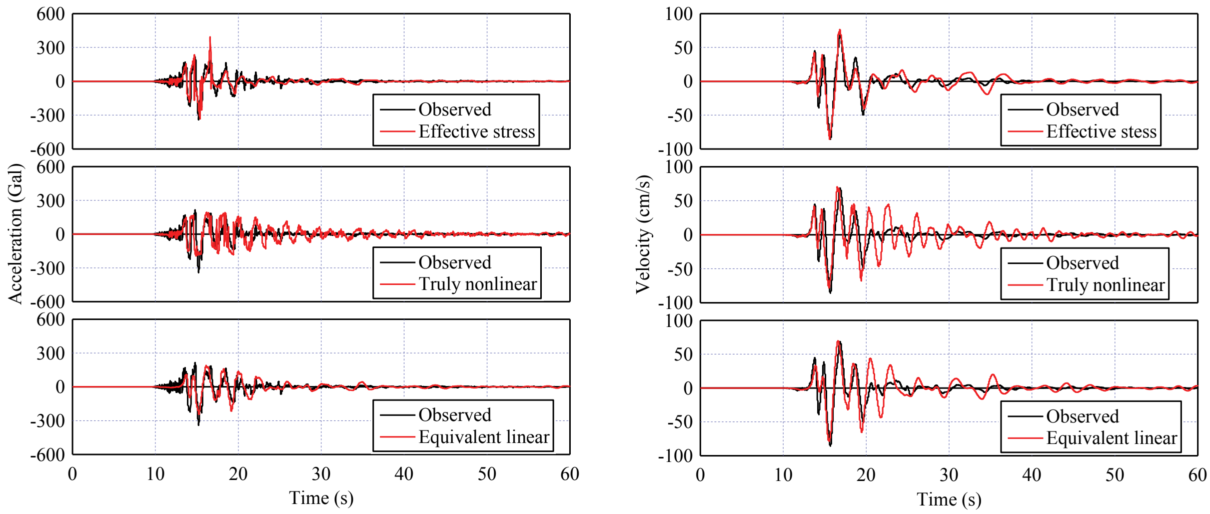

Fig. 4 – Comparison of radar charts (Values are scale of amplitude.)
(The 1993 Kushiro-oki earthquake)

Radar charts which indicate the ratio of the results of total stress truly nonlinear analysis or equivalent linear analysis to the results of the effective stress analysis obtained by each analytical case are shown in Fig. 4, respectively. Values in the parenthesis under the character string '*STR*' in radar charts are the maximum shear strain obtained by the effective stress analysis. Firstly, the results of total stress truly nonlinear analysis is focused on. Clear differences in the radar chart appear at the case of 0.7 times the amplitude and analytical errors of the maximum acceleration (*PGA*) and the maximum shear strain (*STR*) become about 10% in this analytical case. When the scale of the amplitude increases, an area surrounded by the radar chart line decreases, resulting in decrease in accuracy of the total stress truly nonlinear analysis. In particular, decrease in accuracy of the maximum shear strain (*STR*) and the maximum acceleration (*PGA*) appear clearly in the case of 1.0 time the amplitude. On the other hand, even if the scale increases to 1.0 time the amplitude, the predominant frequency of transfer function ($F_p$) does not change much.




a) Acceleration b) Velocity

Fig. 5 – Earthquake record at Port Island during the 1995 Hyogoken-nambu earthquake (G.L. -83 m)




a) Acceleration b) Velocity

Fig. 6 – Comparison of analytical and observed time histories (Ground surface)
(The 1995 Hyogoken-nambu earthquake)

The results of the equivalent linear analysis are roughly same as the results of the total stress truly nonlinear analysis; analytical accuracy of many indices decreases while the input earthquake motion increases. Decrease in accuracy of the maximum shear strain, however, has begun to show from 0.2 times the amplitude smaller than the amplitude from which accuracy has begun to decrease in the total stress truly nonlinear analysis.

## 4. Validation based on record during the 1995 Hyogoken-nambu earthquake

### 4.1 Site and method of analysis

The vertical array records at Port Island during the 1995 Hyogoken-nambu earthquake (Kobe earthquake) are used. The observation site of the vertical array locates in the northwest corner of Port Island which is a man-made island developed in 1969. Liquefaction occurred in the observation site during Kobe earthquake. The record was obtained by 4 depths, G.L. 0 m, -16 m, -32 m and -83 m (Association for Earthquake Disaster Prevention [11]). The observed acceleration record at the ground surface had notable characteristics; the acceleration amplitude was smaller than that at the base and the waveform did not consist of short-period components. Regarding details of the ground condition in the observation site and the case study of the effective stress analysis using FLIP computer code (Yoshida [12] and Nozu [10], respectively).

Acceleration record at the base for analyses and velocity waveform integrated by acceleration are shown in Fig. 5. The subject of analyses was conducted for the NS components which are the larger component of the two horizontal components. Figure 6 shows acceleration and velocity time histories at the ground surface obtained by the effective stress, total stress truly nonlinear and equivalent linear analyses compared with observed records, respectively. Focusing on the response of the acceleration for the first big waveform around 15 s, the waveform in the equivalent linear analysis succeeds the phase but the maximum value is smaller than the observed record. In the total stress truly nonlinear analysis, the phases of both acceleration and velocity shift and the acceleration amplitude is smaller than the observed record, and moreover a difference from the observed record in the damping tendency of the acceleration waveform after principal motion is observed. The results of the effective stress analysis agrees well with the response around 15 s and damping tendency after principal motion in the observed record, and could more accurately reproduce the observed records than those of the total stress truly nonlinear and equivalent linear analyses.

The effective stress analysis considering the dilatancy of filled sand can express overall decrease and momentary increase of the acceleration amplitude which indicate occurrence of liquefaction. While the effective stress analysis succeeded well the small amplitude which is shown in the observed velocity record after the peak around 15 s, the results of the other two analytical methods show a smaller damping tendency of the amplitude and a difference from the observed records. The maximum shear strain exceeds 3% and this case study shows advantages of the effective stress analysis well in the large-strain region the same as the case study of the 1993 Kushiro-oki earthquake. Ten analytical cases from 0.1 times to 1.0 time at an interval of 0.1 times based on the amplitude of the acceleration records at the base, are conducted and the results of each analysis are evaluated with the radar chart hereafter, the same as the former case study.

### 4.2 Accuracy evaluation by means of radar chart

Radar charts which indicate the ratio of the analytical results to the observed record of each index are shown in Fig. 7. All indices show that the effective stress analysis reproduces the observed values more accurately than those of the total stress truly nonlinear and equivalent linear analyses judging from shape of the radar charts. The SI values (*SI*) of the total stress truly nonlinear and equivalent linear analyses, however, are closer to observed value than that of the effective stress analysis. Regarding the maximum acceleration (*PGA*), the effective stress becomes larger than the observed value and the total stress truly nonlinear and equivalent linear analyses become smaller than the observed value. This is caused by a spike-shaped waveform of around 17 s resulting in the larger acceleration response in the effective stress analysis than the observed value. Then smaller acceleration response around 15 s in the total stress truly nonlinear and equivalent linear analyses than the observed value is also one of the causes. The maximum velocity (*PGV*) in the radar chart obtained by the total stress truly nonlinear and equivalent linear analyses are nearly equal to the observed record but the PSI values obtained by both analyses are significantly larger than the observed record. These results correspond to the velocity waveform; the maximum velocity (*PGV*) obtained by the analyses is equal to the observed record but the amplitude after the peak is overestimated. The differences of the predominant frequency of the transfer function ($F_p$) and the acceleration for the instrumental seismic intensity ($a_0$) between the results of the total stress truly nonlinear analysis and the observed records appear clearly and the results of equivalent linear analysis could more accurately reproduce the observed records.

Radar charts which indicate the ratio of the results of the total stress truly nonlinear analysis or those of equivalent linear analysis to the results of the effective stress analysis of analytical cases are shown in Fig. 8, respectively. Firstly, focus attention on the results of total stress truly nonlinear analysis. The maximum acceleration (*PGA*) and the maximum shear strain (*STR*) are slightly larger than 1.0 in the 0.3 times the amplitude but these are quite small in the 0.4 times the amplitude. All indices except the predominant frequency of transfer function ($F_p$) in the case of 0.5 times the amplitude are smaller than 1.0, so that the total stress truly nonlinear analysis shows clearly lower accuracy than the effective stress analysis. These results in the case of 0.5 times the amplitude reflect almost the same tendency in the case of the 1.0 time the amplitude in the 1993 Kushiro-oki earthquake. The maximum shear strain is 1.71% in this case (0.5 times the amplitude) and that is 1.28% in the case of the 1993 Kushiro-oki earthquake (1.0 time the amplitude), then both strain levels are to the same degree.

When the scale of the amplitude increases than 0.7 times the amplitude, the PSI value and the SI value are overestimated and the tendency of the results are different from the results in the case of the amplitude smaller than 0.5 times. It seems that when the maximum shear strain in the effective stress analysis becomes larger than 2%, the influence of the stiffness softening due to soil liquefaction becomes larger.

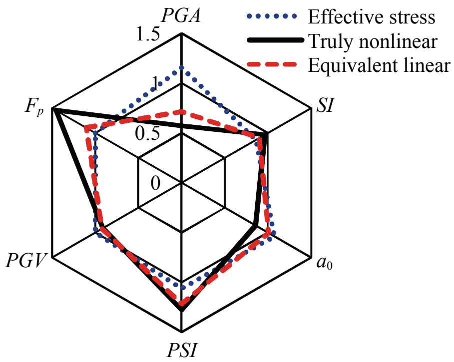



Fig. 7 – Comparison of radar chart (Analytical result/Observed value)
(The 1995 Hyogoken-nambu earthquake)

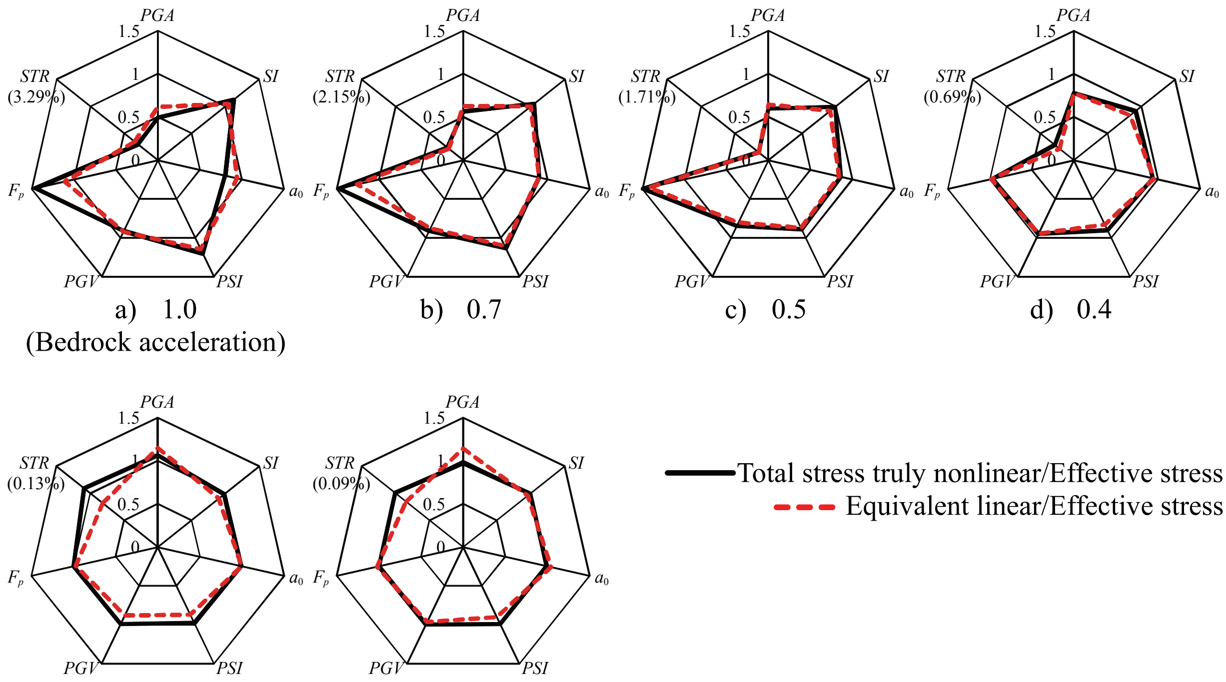



Fig. 8 – Comparison of radar charts (Values are scale of amplitude.)
(The 1995 Hyogoken-nambu earthquake)

The strain level where the accuracy decreases in the equivalent linear analysis is smaller than the strain level in the total stress truly nonlinear analysis. Note that the cause of this lower accuracy in the small-strain region may be attributed to initial conditions which cannot be considered in the equivalent linear analysis as mentioned above. On the other hand, in the large-strain region, where the scale of the amplitude becomes bigger than 0.4 times the amplitude and the maximum shear strain in the effective stress analysis exceeds 0.69%, the equivalent linear analysis has the advantage over the total stress truly nonlinear analysis in results of the predominant frequency of transfer function ($F_p$), acceleration for the instrumental seismic intensity ($a_0$) and maximum acceleration (*PGA*).

## 5. Error of each index and applicability of analytical methods

Relationships between the maximum shear strain obtained by the effective stress analysis and the ratio of the results of total stress truly nonlinear analysis or equivalent linear analysis to the results of effective stress analysis are divided for each index and shown in Fig. 9. These figures show changes of accuracy of each index corresponding to the strain level and a result of the instrumental seismic intensity ($I_{JMA}$, Eq. (2)) as well as the seven indices shown in the radar chart is also added. In this chapter, accuracy of the total stress truly nonlinear and equivalent linear analyses against the effective stress analysis are evaluated, and their accuracy is expressed such that accuracy against the effective stress analysis, for instance, decreases by 20% accordingly as the ratio of the index becomes 0.8. Based on these relationships, the eight indices are separated into three groups: indices which are sensitive to the increase of strain (Group 1); indices which are hardly affected by the increase of strain (Group 2); and indices which have intermediate sensitiveness (Group 3). Then the results of the previous two analytical cases are shown together in the same figure.

Each ratio in all of the indices except instrument seismic intensity ($I_{JMA}$) largely fluctuates when the maximum shear strain of effective stress analysis exceeds 1%. This phenomenon is not shown in the case of the 1993 Kushiro-oki earthquake in which the maximum shear strain equals 1.28%, but in the case of the 1995 Hyogoken-nambu earthquake when the maximum shear strain exceeds 2%. This is caused by rapid stiffness softening due to soil liquefaction. The following consideration focuses on the strain range of smaller than 1% where such influence is small.

The first indices which are sensitive to the increase of strain (Group 1) are 2 indices; maximum acceleration (*PGA*) and maximum shear strain (*STR*). As shown previously in radar charts, the analytical accuracy of these indices decrease firstly when input acceleration increase. Then the accuracy of these indices becomes low monotonously when the maximum shear strain exceeds 0.1%, and there are significant decreases of accuracy in 1% in the maximum shear strain.

Then indices which are hardly affected by the increase of strain (Group 2) are 2 indices; the instrument seismic intensity ($I_{JMA}$) and the prominent frequency of transfer function ($F_p$). Accuracy of the former index hardly changes according to the case studies and the analytical methods. Accuracy of the latter index decrease by 10% in about 1% of the maximum shear strain.

Four indices have intermediate sensitiveness; acceleration for instrumental seismic intensity ($a_0$), maximum velocity (*PGV*), the SI value (*SI*) and the PSI value (*PSI*). Accuracy of almost all indices decreases by 20% in 1% the maximum shear strain.

Because the maximum shear strain and maximum acceleration are instant results, the analytical accuracy does not change monotonously according to an increase of input acceleration but changes while repeating the increase and decrease. Thereafter, the analytical accuracy decreases particularly if the strain level becomes large. On the other hand, the accuracy of many indices such as the PSI value increases monotonously according to increased input acceleration until 1% of the maximum shear strain because they are integral values in the time region or frequency region.

If analytical accuracy is evaluated by the maximum acceleration such as in the conventional method and difference of 10% from the effective stress analysis is used as the tolerance of analytical accuracy, the applicability limit of the total stress truly nonlinear analysis is approximately 0.1% the maximum shear stain and that of equivalent linear analysis is smaller than 0.1% the maximum shear strain. Concerning all indices except high sensitivity indices, analytical accuracy of equivalent linear analysis is not always lower than that of total stress truly nonlinear analysis, in particular, in the large-strain region. If it is possible to accept difference of 20% from the effective stress analysis, total the stress truly nonlinear could be applied until 1% maximum shear strain for evaluating earthquake motion indices except high sensitivity indices.

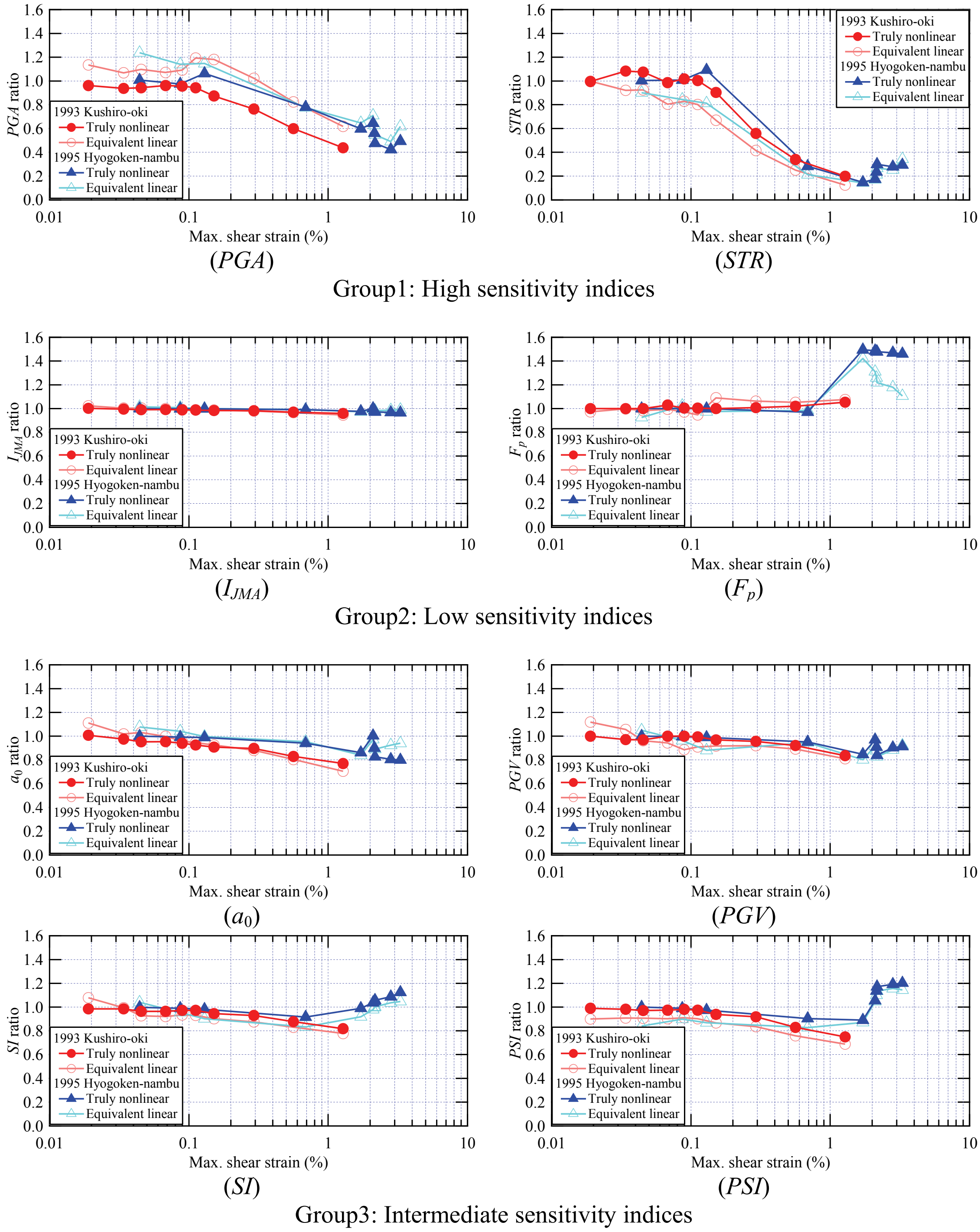



Fig. 9 – Maximum shear strain vs. error ratio of each index

## 6. Conclusions

The way to express earthquake motion indices which have been employed for evaluation of the earthquake damage with the radar chart was proposed as an evaluation method of accuracy of the seismic response analysis of a ground. Then two case studies in which the effective stress analysis indicated high reproducibility to the observed records were conducted to validate the applicability of total stress truly nonlinear and equivalent linear analyses with the radar chart which consists of seven indices. The following conclusions are obtained:

1) To use the radar chart for evaluating the accuracy of the seismic response analysis of a ground can show visually the analytical method could reproduce the observed records in good balance against various earthquake motion indices. Judging from the shape of the radar chart in the two case studies that targeted vertical array records, the effective stress analysis showed the best simulation and many indices obtained by the total stress truly nonlinear and equivalent linear analyses are underestimated compared to the recorded values.
2) If a difference of 10% from the effective stress analysis is used as the tolerance of analytical accuracy, the accuracy of maximum acceleration and maximum shear strain decrease in case the maximum shear strain exceeds 0.1% in the effective stress analysis. Therefor the applicability of total stress truly nonlinear is limited to 0.1% of maximum shear strain.
3) The applicability limit of the analytical methods which differs depending on earthquake indices is cleared. The compatible-strain ranges of the total stress truly nonlinear and equivalent linear analyses differ depending on the purpose of analysis. The applicability limit of the total stress truly nonlinear and equivalent linear analyses should not be defined based on conventional uniform criteria such as the maximum acceleration.
4) The analytical accuracy of the equivalent linear analysis is not always lower than that of the total stress truly nonlinear analysis, in particular, in the large-strain region.

## 7. References

[1] Ishihara K (1982): Evaluation of Soil Properties for Use in Earthquake Response Analysis, *Proc. 9th International Symposium on Numerical Models in Geomechanics*, Zurich, 237-259.

[2] Yoshida N (2014): *Seismic Ground Response Analysis*, Springer.

[3] Housner G W (1965): Intensity of Earthquake Ground Shaking Near the Causative Fault, *Proc. 3rd World Conference on Earthquake Engineering*, Vol. I, III-94-III-115.

[4] Katayama T, Sato N, Ohbo N, Kawasaki M and Saito K (1986): Ground Shaking Severity Detector by Use of Spectrum Intensity (SI), *Proc. 7th Japan Earthquake Engineering Symposium*, 373-378.

[5] Japan Meteorological Agency (1996): *Know Seismic Intensity*, *Basic Knowledge and the Utilization*, Gyosei Corp. (in Japanese).

[6] Nozu A and Iai S (2001): Consideration of Earthquake Motion Index for Immediate Damage Estimation of Quay Wall, *Proc. 28th Annual Conference of the Kanto Branch of JSCE*, 18-19 (in Japanese).

[7] Iai S, Matsunaga Y and Kameoka T (1992): Strain Space Plasticity Model for Cyclic Mobility, *Soils and Foundations*, Vol. 32, No. 2, 1-15.

[8] Yoshida N (2010): DYNEQ A Computer Program for DYNamic response analysis of level ground by EQuivalent linear method Version 3.34, Revised from Original Version (May 1995), http://www.civil.tohoku-gakuin.ac.jp/yoshida/computercodes/eqcode.html.

[9] Iai S, Morita T, Kameoka T, Matsunaga Y and Abiko K (1995): Response of a Dense Sand Deposit during 1993 Kushiro-oki Earthquake, *Soils and Foundations*, Vol. 35, No. 1, 115-131.

[10] Nozu A (2007): Strong Motion Simulation Using Both Nonlinear Parameters and Effective Stress Analysis, *JSCE Journal of Earthquake Engineering*, Vol. 29, 114-122 (in Japanese).

[11] Association for Earthquake Disaster Prevention (1998): *Strong motion array observation*, No.3 (in Japanese).

[12] Yoshida N (1995): Earthquake Response Analysis at Port Island during the 1995 Hyogoken-nanbu Earthquake, *Tsuchi-to-Kiso*, the Japan Geotechnical Society, Vol. 43, No. 10, 49-54 (in Japanese).