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Original paper

Progress of Soil Nonlinearity Researches of Recent Years in Russia and Taiwan

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Abstract: Relevance. Soil nonlinearity has a significant influence on result seismic effect at strong motions which differ from weak and moderate ones. Practice of construction faced with adequate account of nonlinear effect in weak soils and demand techniques for design parameters assessment. Researches of recent years in the field of soil nonlinearity may enrich each other and find the main way for effective practices and building codes regularization. **The aim of this work** is allocation of parameters for nonlinearity description and corresponding techniques development. **Methods.** Field soil response analysis with sources of different power in conjunction with strong motion records were analyzed by means of regression analysis and other machine learning techniques. Mathematical modeling includes multiple reflected waves analysis technique and finite elements modeling. **Results.** The parameters that are closely related to the absorption and soil nonlinearity were identified. The empirical formulas connecting the areas of normalized and real spectra with the parameters of seismic loadings were obtained using regression analysis. The differences of absorption mechanism in dispersed (soft) and rocky soils were defined. **Conclusion.** The models of ground strata behavior in the case of variable intensity of dynamic action on the basis of consideration of the real area of the spectrum and the average value of the frequency, characterized by a linear and nonlinear elastic-inelastic deformation of the soils are offered. Degree of nonlinearity (DNL) metric may be efficiently used for stress-strain curve assessment, and in the absence of strong earthquakes records it can be applied for powerful seismic sources records analysis what determines the direction of future research.

Keywords: earthquake, intensity, nonlinear, site effect, strong motion databases.

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ГЕОФИЗИКА

DOI: 10.46698/VNC.2020.28.93.007

Оригинальная статья

Прогресс исследований за последние годы нелинейных свойств грунтов в России и на Тайване

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Резюме: Актуальность работы. Нелинейные свойства грунтов оказывают существенное влияние на результат сейсмического воздействия при сильных движениях, которые отличаются от слабых и умеренных. Практика строительства столкнулась с необходимостью адекватного учета эффекта нелинейности в слабых грунтах и методики оценки проектных параметров. Исследования нелинейных свойств грунтов проведенные за последние годы могут обогатить друг друга и найти основной путь для эффективной практики и регуляризации строительных норм. **Целью работы** является выделение параметров для описания нелинейности и разработки соответствующих методик. **Методы исследования.** Был проанализирован отклик грунта в полевых условиях с источниками различной мощности в сочетании с записями сильных движений с помощью регрессионного анализа и других методов машинного обучения. Математическое моделирование включает в себя метод анализа многократно отраженных волн и моделирование методом конечных элементов. **Результаты.** Были определены параметры, тесно связанные с поглощением и нелинейностью грунтов. С помощью регрессионного анализа были получены эмпирические формулы, связывающие области нормированного и реального спектров с параметрами сейсмических нагрузок. Выявлены различия механизма поглощения в дисперсных (рыхлых) и каменистых грунтах. **Выводы**. Предложены модели поведения наземных пластов при переменной интенсивности динамического воздействия на основе учета реальной площади спектра и среднего значения частоты, характеризующейся линейной и нелинейной упруго-неупругой деформацией грунтов. Критерий степени нелинейности (DNL) может быть эффективно использован для оценки кривой напряжения-деформации, а в отсутствие записей сильных землетрясений он может применяться для анализа записей мощных сейсмических источников, определяющих направление будущих исследований.

Ключевые слова: землетрясение, интенсивность, нелинейность, условия площадки, базы данных сильных движений.

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1 Introduction

Implementation of the existing approaches in seismic hazard assessment is associated with appreciable errors due to the complex effects observed during strong earthquakes related to the heterogeneity of the medium seismic properties, complex topography of the daylight and underground surfaces and nonlinearity of soils. The aim of this work is to analyze the modern concepts of taking into account nonlinearity of soils in seismic microzonation in Russia and strong ground motion researches in Taiwan.

Soil nonlinearity effects are one of the important influences on earthquake strong ground motion, are commonly recognized in the dynamic loading of soils from geotechnical models. It is mainly caused by interaction of seismic waves with shallow softer material, and accomplished as a drop in shear-wave velocity [Aguirre, Irikura, 1997; Nikolaev, 1967] and increasing damping ratio of the shallow soil layers. The significant features of soil nonlinearity include de-amplification of the soil amplification factor [Boore et al., 1989; Darragh, Shakal, 1991a; 1991b], a drop in dominant frequency [Wen et al., 1994; 1995; Beresnev et al., 1995a; 1995b; Zaalishvili, 1996] and de-amplification of the high frequency spectrum [Wen et al., 2006; Zaalihvili, 2009], or even liquefaction of the shallow soil layers. Seismic response could be overestimated during strong motions when only linear behavior is considered for strong motion simulation or strong motion prediction techniques.

2 Construction of seismic microzonation for Russia

In Russian school of engineering seismology instrumental method is traditionally considered as the main method of seismic microzonation. This method urges to solve a forecast problem of forming earthquake intensity. However the calculational method allows modeling any definite conditions of area and impact features and is often characterized as more reliable. Usage of both methods together significantly increases the results validity.

Explosive effects of high power allows to study the behavior of real media in conditions most similar to earthquakes. The intensity increment ΔI of the soils of the zoned territory is calculated by the formula at usage of weaker explosions [Zaalishvili, 2009]:

$$\Delta I=3.3 lg A_i/A_0, \qquad (1)$$

where: A_i, A_0 are vibrational amplitudes of the investigated and reference soils, respectively.

Despite the prevalence of explosive sources in scientific and applied research, we note that the energy spent on the formation of elastic seismic waves makes up only 3-5% of the total explosion energy. Execution of powerful explosions on the territory of cities, settlements or near the responsible buildings is connected with large and often insurmountable obstacles (technical and ecological problems, safety problems, labouriousness and economical expediency) and practically isn't used nowadays. This leads to the wide spreading of nonexplosive vibration sources [Zaalishvili, 2012].

The features of seismic microzonation methods development led to the situation when the tool of elastic wave excitation with the help of low-powered sources (for example, hammer impact with m = 8-10 kilograms) has become the most wide spread in order to determine S- and P-wave propagation velocities in typical types of soils of territory. Velocity values are used in order to calculate the intensity increment using the tool of seismic rigidities by S. V. Medvedev [Zaalishvili, 2009]:

$$\Delta I = 1.67 \lg \rho_i V_i / \rho_0 V_0 \qquad (2)$$

where: $\rho_0 V_0$ and $\rho_i V_i$ is the product of the soil consistency and S-wave velocity – seismic rigidities of the reference and the investigated soil, respectively.

The given approach of S. V. Medvedev gained unexpectedly wide extension in 70-es of the 20 century due to its simplicity and efficiency (former USSR countries and countries of Eastern Europe, USA, Chile, Italy, India).

2.1 Seismic microzonation based on accounting of soil nonlinear properties

It was found that reliability of the method considerably increases at usage of modern powerful impulsive energy sources (Fig. 1).

The lowering of final results quality is to a certain extent caused by the fact that in the tool of "intensities" the seismic effect dependence in soils on frequency or "frequency discrimination" of soils [Zaalishvili, 2000] and also the origin of typical "nonlinear effects" at strong movements isn't taken into account. A. B. Maksimov tried to remedy this deficiency by developing the tool, where frequency peculiarities of soils were taken into account [Zaalishvili, 2009]:

$$\Delta I = 0.8 \lg \rho_0 V_0 f_0^2 / \rho_i V_i f_i^2 \qquad (3)$$

where: f_0, f_i are predominant frequencies of reference and investigated soils, respectively.

A. B. Maksimovs' tool didn't find wide distribution, as frequency differences of soil vibrations with sharply different strength properties (at usage of traditional for the seismic exploration of small depths low-powered sources) were insignificant and the calculation results on the formulas (2) and (3) were practically similar [Zaalishvili, 2000].

Intensity increment was determined by the following formula [Zaalishvili, 2000]:

$$\Delta I = 0.8 \lg \rho_0 V_0 f_{wa0}^2 / \rho_i V_i f_{wai}^2 \qquad (4)$$

where: f_{wa0}, f_{wai} are weighted-average vibration frequencies of reference and investigated soils, respectively.

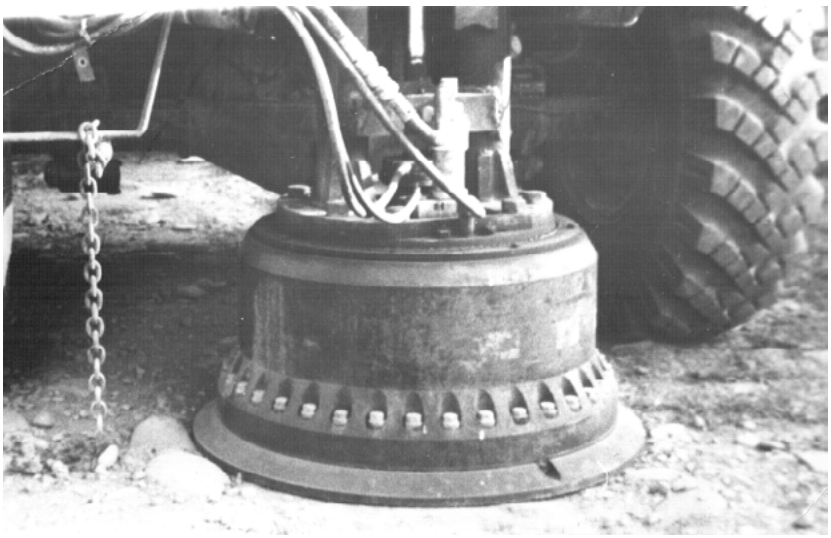

Fig. 1. Surficial gas-dynamical pulse source (SI-32). /
Рис. 1. Поверхностный газодинамический импульсный источник (СИ-32)

Weighted-average vibration frequency of soils was calculated at that on the formula [Zaalishvili, 1987; 2012]:

$$f_{wa}=\sum A_i f_i/\sum A_i \quad (5)$$

where: A_i and f_i are the amplitude and the corresponding frequency of vibration spectrum, respectively.

The comparison of the absorption and nonlinearity indices with the corresponding spectra of soil vibrations shows that at higher absorption the spectrum square prevails in low frequency (LF) field and at high nonlinearity it prevails in high frequency (HF) field of the spectrum. In other words, the presence of absorption is displayed in additional spreading of LF spectrum region, and the presence of nonlinearity – in spreading of HF range.

All the mentioned allowed to obtain the formula for calculation of intensity increment on the basis of taking into account nonlinear – elastic soil behavior or elastic nonlinearity (at usage of vibration source) [Zaalishvili, 2012]:

$$\Delta I=3lg\, A_i f_{wai} / A_0 f_{wa0}, \quad (6)$$

where: $A_i f_{wai}$, $A_0 f_{wa0}$ are the products of spectrum amplitude on weighted-average vibration frequency of investigated and reference soils, respectively.

The formula (5) characterizes soil nonlinear – elastic behavior at the absence of absorption.

If the impulsive source is used at seismic micro-zonation method (SMZ) then the formula will have the form [Zaalishvili, 2009]:

$$\Delta I=2lg A_i i f_{wai}/A_0 f_{wa0}, \quad (7)$$

2.2 Seismic microzonation based on accounting of soil inelastic properties

The estimation of potential soil nonelasticity adequately and physically proved at intensive seismic loadings is the most important problem of seismic microzonation as soil liquefaction and differential settlement of the constructions are observed at strong earthquakes (Niigata, 1966; Kobe, 1995).

For direct assessment of soil nonelasticity the specific scheme of the realization of experimental investigations (fig. 2a) with gas-dynamic impulsive source GSK-6M (with two radiators) was used. Chosen longitudinal profile location allowed making impact sequentially by two emitters from near and somewhat far radiation zones. The HF component that quickly attenuates with distance (fig. 2 b) prevails in the spectrum of soil vibrations, caused by near emitter. In a case of distant emitter impact the LF component predominates in the spectrum of vibrations (fig. 2 c). In other words, at nonlinear-elastic deformations the main energy is concentrated in the HF range of spectrum and at nonelastic – in the LF range. The signal spectrum has the symmetrical form in the far and practically linear-elastic zone.

Elastic linear and nonlinear vibrations are characterized for the given source by the constancy of the real spectrum square, which is the index of definite source energy value, absorbed by soil (which is deformed by the source). The analysis of strong and destructive earthquake records and also the analysis of specially carried out experimental impacts showed that at nonelastic phenomena spectra square of corresponding soil vibrations is not the constant value. It can decrease and the more it decreases, the less the soil solidity and the greater the impact value is [Zaalishvili, 2012].

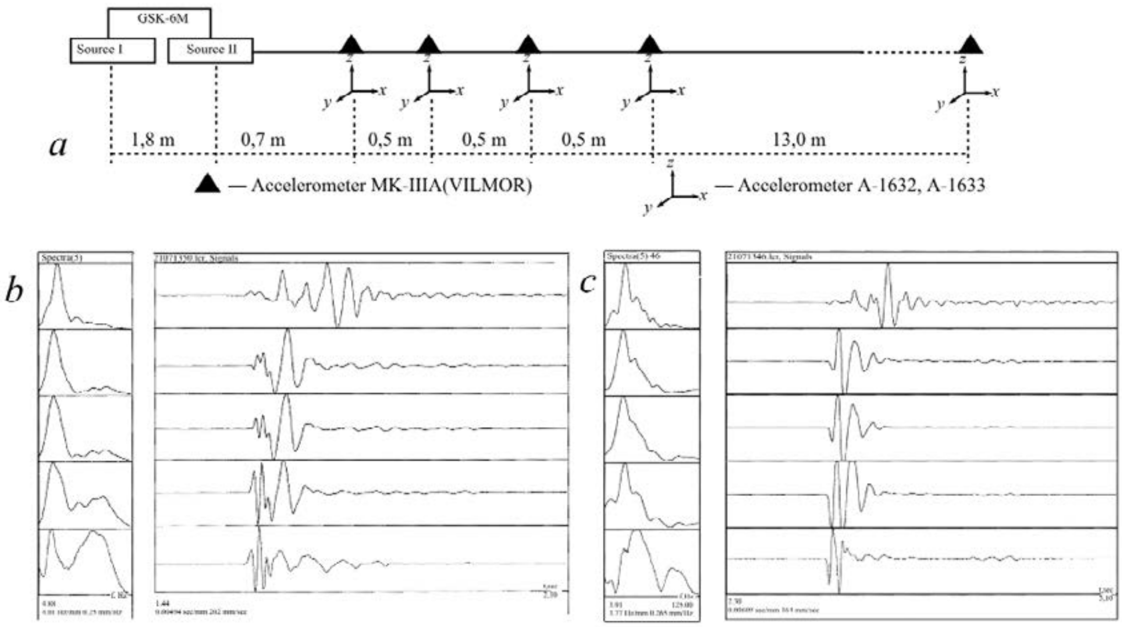

Fig. 2. Investigation of site spectral features by means of GSK-6M seismic source: a) experiment scheme; b) records of first source impact; c) records of second source impact. /
Рис. 2. Исследование спектральных особенностей площадки с помощью сейсмического источника ГСК-6М: а) схема эксперимента; б) записи первого источника воздействия; в) записи второго источника воздействия.

At usage of vibratory energy source, the whole number of new formulas [Zaalishvili, 2009] was obtained in order to assess soil seismic hazard with taking into account the amount of their nonelasticity:

$$\Delta I=2.4\ [\lg\ (S_{ri})_{n}\ (S_{r0})_{d} / (S_{ri})_{d}\ (S_{r0})_{n}], \qquad (8)$$

where: $(S_{ri})_{n,\,d}$ $(S_{r0})_{n,\,d}$ are the squares of real spectra of soils under investigation and reference soils in near and distant zones of the source, respectively.

$$\Delta I=3.3\lg\ [\ (A_i f_{awi})_{n}\ (A_0 f_{aw0})_{d} / (A_i f_{awi})_{d}\ (A_0 f_{aw0})_{n}], \qquad (9)$$

where: $(A_i\ f_{awi})_{n,\,d}$ and $(A_0\ f_{aw0})_{n,\,d}$ are the amplitudes and weighted-average frequencies of soils under investigation and reference soils in near and distant zones of the source, respectively.

If a powerful impulsive source is used the offered formulas will be as following:

$$\Delta I=1.2\ [\lg\ (S_{ri})_{n}\ (S_{r0})_{d} / (S_{ri})_{d}\ (S_{r0})_{n}], \qquad (10)$$

where: $(S_{ri})_{nd}$ and $(S_{r0})_{nd}$ are the squares of real spectra of soils under investigation and reference soils in near and distant zones of the source, respectively;

$$\Delta I=2\lg\ [\ (A_i f_{awi})_{n}\ (A_0 f_{aw0})_{d} / (A_i f_{awi})_{d}\ (A_0 f_{aw0})_{n}], \qquad (11)$$

where: $(A_i\ f_{awi})_{n,\,d}$ and $(A_0\ f_{aw0})_{n,\,d}$ are the amplitudes and weighted-average frequencies of soils under investigation and reference soils in near and distant zones of the source, respectively.

The formulas (8) and (9) are adequate only for loose dispersal soils. The formulas (8) and (9) were used at SMZ of Kutaisi city territory. Besides, using the formulas (10) and (11) nonelastic deformation properties of soils in full-scale conditions on Novovoronezh APP-2 site were defined more accurately [Zaalishvili, 2009; 2012]. The formulas were obtained based on physical principle that underlies the scheme used at the soil looseness assessment.

2.3 Consideration of the integral motion, taking nonlinear properties of soils into account

Consideration of the integral motion, taking nonlinear properties of soils into account, obviously creates the conditions for their use in seismic microzonation. Soil is the most uncertain factor in all of the cited studies. Therefore, the issues of geotechnical parameters` accounting for various seismological tasks are considered quite seriously all over the world [Seed et al., 1988; Studer, Ziegler, 1986].

In this regard, the consideration of nonlinear phenomena in the soil or the soil – structure system eliminates the existence of an amplification in the form of a traditional constant value [Aubri, Modaressi, 1987], because the latter is based precisely on a linear representation of ground movement.

Let`s consider the example. The table 1 shows the results of comparing the materials from an engineering macroseismic survey of the epicentral zone of the Racha earthquake (Georgia, 1991) and the parameters of the instrumental records obtained under various ground conditions by the SMACH network. Calculations of amplification were carried out using the ratio

$$\delta I = \left\{ \lg \frac{M_1^2 t_{i1} f_{\mathrm{wa}i1}^2}{M_2^2 t_{i2} f_{\mathrm{wa}i2}^2} \sqrt{\frac{a_{i1}}{a_{i2}}} - \lg \frac{M_1^2 t_{01} f_{\mathrm{wa}01}^2}{M_2^2 t_{02} f_{\mathrm{wa}02}^2} \sqrt{\frac{a_{01}}{a_{02}}} \right\}, \quad (12)$$

were δI is nonlinear amplification on varying exposure, $\Delta I = \Delta I_{ni} - \Delta I_{n0}$; ΔI_{ni}, ΔI_{n0} are nonlinear amplification for the investigated and reference soils, respectively, point; M_1, M_2 are the magnitudes of (n) and (n+1) earthquakes, respectively; $t_{i01,}$ t_{i02} – the duration of the vibrations of the studied and reference soils during the (n) and (n + 1) earthquakes (with magnitudes M_1 and M_2), respectively, s; $f_{wai01,}$ $f_{\mathrm{wa}i02}$ – weighted average frequencies of vibrations of the investigated and reference soils at (n) and (n + 1) earthquakes, respectively, Hz; $a_{i01,}$ a_{i02} – vibration acceleration of the investigated and reference soils during (n) and (n + 1) earthquakes, respectively, m/s^2.

Table 1

Engineering and geological conditions of the site	Amplification, ΔI, point with earthquake magnitude		
	M = 3.0	*M* = 5.0	*M* = 5.3
a) macroporous clay, (h = 10.0 m); b) pebbles with sand and clay filler (> 30%, h = 5.0 m); c) slightly weathered limestones	–	–	–
a) weathered limestones (h = 10.0 m); b) slightly weathered limestones	–2.30	–1.48	–0.84

It is clear that the amplification decreases with magnitude of the earthquake increase. This largely explains the significant difference in the features of soil vibrations in the near and far zones. Thus, a small difference in the seismic effect even between soils with very different seismic properties is well known. The nonlinear relationship between the stress and deformation of loose soil causes unequal distortion of the compression and extension phases, an increase in the rarefaction phase in weaker soils, which leads to a dependence of the dynamic indicators of soil motion on the impact energy.

2.4 Calculational method of seismic microzonation

In order to analyze the features of soil behavior with introduction of definite engineering – geological structure characteristics of investigated site as initial data the calculational method of seismic microzonation is used: values of shear wave velocities, modulus of elasticity, index of extinction, power of soil layers, their consistency etc. Calculational method includes the following techniques: thin-layer medium, multiple-reflected waves, finite-difference method, finite-elements analysis (FEA) and others.

Calculational method allows modeling virtually any conditions that are observed in the nature. The requirements of practice however reduced to the necessity of calculation of soil vibrations for nonlinear-elastic and nonelastic deformation conditions. Solving such a problem it is assumed that elastic half-space behaves as linear-elastic medium and at intensive seismic or dynamic impacts the covering soil stratum displays strong nonlinear properties.

Received instrumental stress-strain dependences can be applied, for example, for plastic clay soil shown in Fig. 3. Offered by A. V. N ikolaev [Nikolaev, 1987; Zaalishvili, 2009] conception of the so-called soil bimodularity is taken into account in that dependence [Zaalishvili, 2009]. Considerable differences in “weak” soils behavior at compression and extension underlie in the phenomenon. Such soil is characterized at extension by very small modulus of shearing.

Solving of the given nonlinear problem for soils in the analytic form is usually based on considerable assumptions due to the complication of adequate accounting of behavior features of such complicated system as the soil. Thus, the numerical solving of nonlinear problems on the present-day stage of knowledge is the most proved under the condition that the data of field or laboratory investigations are considered in these or those connections [Zaalishvili, Otinashvili, 2000].

So, the basis for solution of calculation nonlinear problems is the correlation determined using experimental investigations. Otherwise stated, programs for solving of calculation nonlinear problems are in essence analytical-empirical. Such programs like SHAKE, NERA etc. are the most adequate [Bardet, Tobita, 2001].

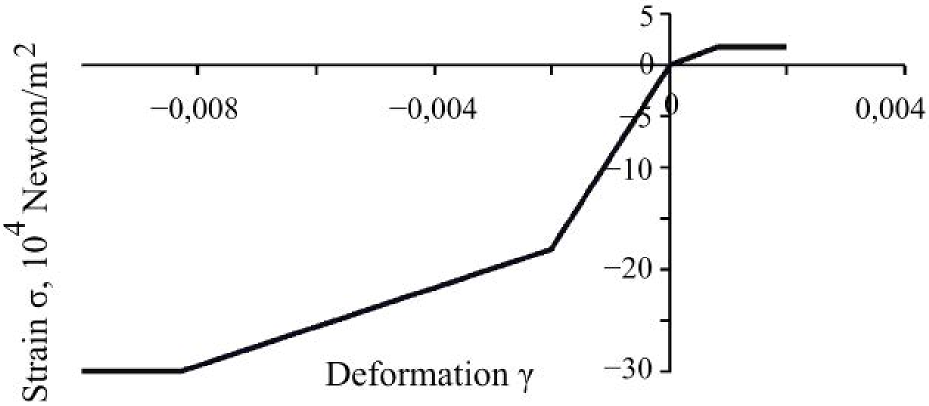

Fig. 3. Instrumental stress-strain curve, showing property of soil bimodularity. /
Рис. 3. Инструментальная кривая напряжения-деформации, демонстрирующая свойства бимодулярности грунта.

It was assumed to modify multiple reflected waves technique for nonlinear effect accounting. Let's suppose that we have the seismic wave, which falls on the soil thickness surface. Let's assume that soil thickness is nonlinear absorptive unbounded medium with the density ρ and S-wave propagation velocity v_S. At small deformations the value of shear modulus G will be maximum for the given soils:

$$G=G_{max}=\rho\, v_S^2 \qquad (13)$$

At the deformation increase the value G remains constant at first but at reaching some value (which is definite for each material or soil) the value G considerably changes, i. e. the soil begins to display its nonlinear properties. At the continued deformation increase the growth of stresses decelerates and then can remain unchanged until material destruction or hardening, i. e. until structural condition change.

As the main soil index, which characterizes its type and behavior at intensive loads, the value of plasticity PI was chosen. The parameters, which are necessary for calculations, are determined on basis of empirical ratios [Ishibashi, Zhang, 1993; Zaalishvili, Otinashvili, 2000]:

$$k(\gamma, PI) = 0{,}5\left\{1 + \tanh\left[\ln \frac{0{,}000102 \; + n(PI)}{\gamma}\right]^{0{,}492}\right\}, \qquad (14)$$

where:

$$n(P_I) = \begin{cases} 0{,}0 & \text{for} \quad \mathrm{PI} = 0, \\ 3{,}37 \cdot 10^{-6} PI^{1{,}404} & \text{for} \quad 0 < PI \le 15, \\ 7{,}0 \cdot 10^{-7} PI^{1{,}976} & \text{for} \quad 15 < PI \le 70, \\ 2{,}7 \cdot 10^{-5} PI^{1{,}115} & \text{for} \quad PI > 70 \ ; \end{cases}$$

$$d = 0{,}272\left\{1 - \tanh\left[\ln\left(\frac{0{,}000556}{\gamma}\right)^{0{,}4}\right]\right\} e^{-0{,}0145 PI^{1{,}3}} .$$

Then the change of shear modulus is determined on basis of the ratio

$$G/Gmax=k\ (\gamma,\ PI)\ (\sigma)\ d, \qquad (15)$$

where G is the current shear modulus, σ is normal stress.

Seismic energy absorption is calculated by the formula

$$\xi=0.3331+\exp\ (-0.0145PI1{,}3)/2\ [0.586\ (G/Gmax)\ 2-1.547G/Gmax+1], \qquad (16)$$

On the basis of the given ratios and introduced by us ratios for determination of necessary indices (normal stress, deformation etc), nonlinear version of the program ZOND was worked out [Zaalishvili, 2009]. From the database of strong motions AGESAS, which was formed by us, the accelerogram, which was recorded on rocks in Japan, with the characteristics (magnitude, epicentral distance, spectral features etc.) similar to the territory of Tbilisi city, was chosen as the accelerogram, given into the bedrock.

The analysis of the results of linear and nonlinear calculations models of definite areas of Tbilisi city territory confirms the adequacy of calculations to the physical phenomena, which were obtained in soils at intensive loads (fig. 4). With the increase of seismic impact intensity the nonlinearity display increases. Absorption grows simultaneously. Hence the resulting motion at quite high impacts levels can be lower than the initial level.

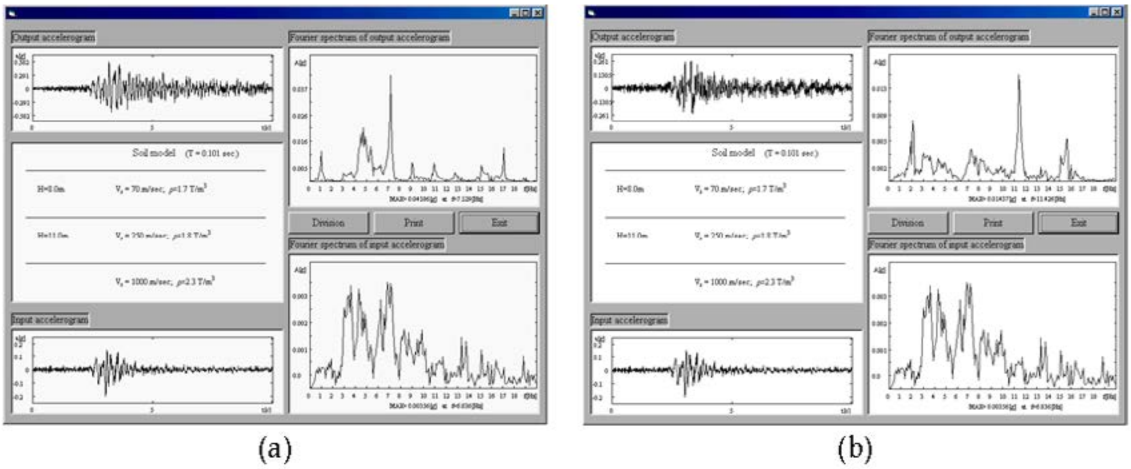

Fig. 4. Results of calculations using multiple reflected waves' tool in linear (a) and nonlinear (b) cases. / Рис. 4. Результаты расчетов с использованием способа многократно отраженных волн в линейном (а) и нелинейном (б) случаях.

It corresponds to the fact, which is known on the results of analysis of strong earthquake consequences, which happened in recent years (for example, Northridge earthquake, 1994).

The problem of the determination of soil massif response on dynamic impact with taking soil nonlinear properties into account can be solved by usage of finite element method (FEM) in the following way [Zaalishvili, 2009]. Soil medium is represented in the form of two-dimensional massif, which is approximate by triangular finite elements. The net, which consists of triangular elements, allows to describe quite accurately any relief form and form of the layer structure of soil massif with its physics-mechanical parameters.

Within finite element the soil is homogeneous with inherent to its characteristics, which vary in time depending on impact intensity. Earthquake accelerogram of horizontal or vertical direction, which is applied, as a rule, to the foundation of soil massif, is used as the impact. Soil is in the conditions of plane deformation and it is considered as an orthotropic medium. Axes of the orthotropy coincide with the directions of main strains [Zaalishvili, 2012]. The problem of nonlinear dynamics of soil massif is solved by means of the consecutive determination of mode of deflection of the system on the previous step. The system is linear-elastic on each step.

2.5 Instrumental-calculational method of seismic microzonation

In recent years a new «instrumental-calculational» method of SMZ (per se simultaneously having the features of both instrumental and calculational method) which includes tool of «instrumental-calculation analogies» has been developed in Russia in recent years [Zaalishvili, 2009]. Its usage is based on direct usage of modern databases of strong movements.

As a basis at realization of tool instrumental database of strong movements, registered in definite soil conditions, is used. As a result of given database with the help of numerical calculations it is possible more or less safely to forecast behavior of these or those soils (or their combination) for strong (weak) earthquakes with typical characteristics for the investigated territory (magnitude, epicentral distance, focus depth etc.).

3 Strong ground motion researches considering soil nonlinearity in Taiwan

Overestimating seismic response during strong motions might happen when applying only linear behavior for strong motion simulation or strong motion prediction techniques. Previous studies mostly used soil-to-rock spectral ratio method to evaluate soil nonlinearity [Wen, 1994; Wen et al., 1994; Beresnev et al., 1995a; 1995b]. The nonlinear site effects are then more common observed than previously recognized in strong-motion seismology [Beresnev, Wen, 1996]. However, suitable reference rock sites were very hard to get especially during wide range liquefaction occurred during large earthquake. Meanwhile, single station H/V spectral ratio (HVSR) method could qualitatively identify soil nonlinearity response from spectral difference between strong against weak motions of strong motion data of Large Scale Seismic Test (LSST), Taiwan array and Port Island, Japan [Wen et al., 2006]. [Noguchi, Sasatani, 2008; 2011] had constructed degree of nonlinearity (DNL) to quantitatively consider soil nonlinearity by summed up the spectrum ratio of strong and weak motions. Moreover, two significant features have been reported from the 2008 Wenchuan, China earthquake, including a dominant frequency drop indicated by short-time-Fourier-transformed HVSR in time-frequency analysis (Fig. 5) and a proportional trend between DNL and peak ground acceleration (PGA) [Wen et al., 2011a]. However, further comparison of relations between soil nonlinearity and site properties of strong motion stations could not be clearly checked owing to the lack of detailed site classification information in Wenchuan near fault region. Therefore, similar methodologies were applied to the 2010-2011 Canterbury, New Zealand, earthquake sequence. In addition to shorter time scaled (co-seismic, Fig. 6) time frequency HVSR, longer time scaled (monthly, Fig. 7) HVSR have also been checked for dominant frequency drop for the Canterbury earthquake sequence. Dominant frequency drop was identified from two larger earthquakes of the sequence and the self-recovery of the soil layer was checked from weak motion HVSR of subsequent aftershocks [Wen et al., 2011b]. [Ren et al., 2017] indicated DNL had positive relation with peak ground acceleration (PGA), peak ground velocity (PGV) and maximum spectral ratio of HVSR etc. from comparing five different methods of quantitatively index of soil nonlinearity. Meanwhile, a convenient strain proxy to explain the stress-strain relation in strong motion nonlinearity effect was established from consider relation between PGA and peak ground velocity (PGV) divided to average shear wave velocity on surface 30 meter's layer (Vs30) (Strain proxy, [Idress, 2011]). The strain proxy was checked from different seismological regions and checked with several different seismic indexes such as PGA, PGV etc. and suggesting it's a useful idea to consider soil nonlinearity [Chandra et al., 2016; Guéguen et al., 2019; Kuo et al., 2019; Derras et al., 2020].

Moreover, in case of considering soil nonlinearity, the effectively technique to deal with it was equivalent linear simulation technique (SHAKE, [Schnabel et al., 1972]), which could consider soil nonlinearity problem in geotechnical engineering filed and addressed in abovementioned Sec. 2.4. While velocity structure, geological material and suitable stress-strain curve were well investigated and constructed for shallow borehole system, linear and nonlinear ground motion simulations could be done from solving wave propagation equation but it had some limitations of deeper structure or multiple layers consideration. Meanwhile, site correction for stochastic ground motion simulation technique from empirical transfer function (ETF, [Huang et al., 2017]) had been verified could provide similar prediction level with traditional ground motion prediction equation

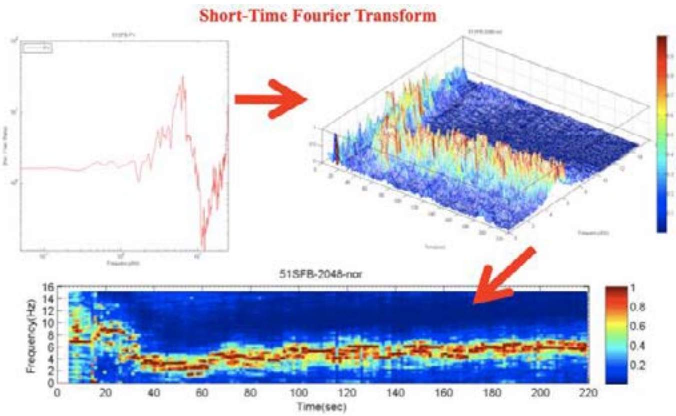

Fig. 5. Short time Fourier transformed HVSR of station 51SFB during Wenchuan, China earthquake [Wen et al., 2011a]. /
Рис. 5. Кратковременное преобразование Фурье HVSR станции 51SFB во время землетрясения в Вэньчуане, Китай [Wen et al., 2011a].

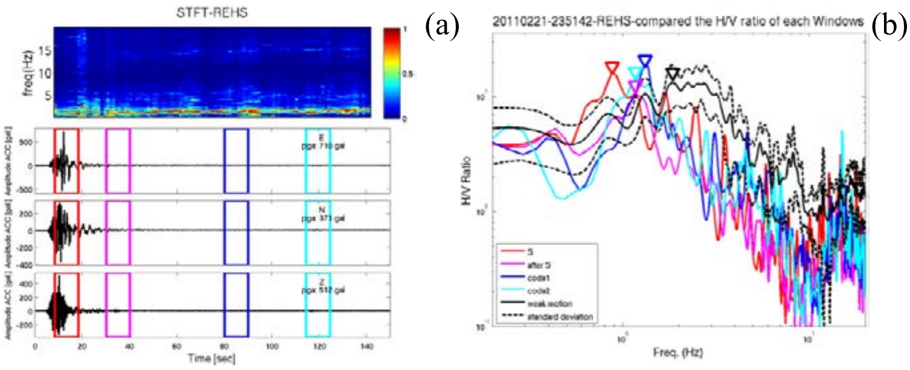

Fig. 6. Time frequency HVSR of each time windows. (red) Shear wave, (purple) after shear wave, (blue and cyan blue) coda waves and (black) averages of weak motions [Wen et al., 2011b]. /
Рис. 6. Частота времени HVSR каждого временного окна. (красным) поперечная волна, (фиолетовая) после поперечной волны, (синяя и голубая) кода-волны и (черные) средние значения слабых движений [Wen et al., 2011b].

(GMPE) and still carry physical meanings. Which means if the seismic parameters were well evaluated in the target region ETF method could provide accurately prediction but still needs to consider more about nonlinearity problems. While the advantages from both simulation techniques was combined to solve nonlinear soil response from following procedure for two borehole seismic arrays in Taiwan (Fig. 9). The simulation process could be described as follows:

Firstly, stochastic simulation would be adjusted from ETF of B class station that would refer to basement rock motion (as imagination of engineering bedrock, EB). Detailed shallow velocity and material of structure above EB would be constructed next and validation of SHAKE process would be made from records of borehole seismograph. Therefore, synthetic motion from first step would be treated as input motion from EB to compute high frequency ground motion simulation with nonlinearity in Taiwan. Finally, ground motion simulation can be performed for moderate magnitude earthquakes by the stochastic point source simulation to rock basement and added the ETF followed [Huang et al., 2017] and can be treated as input motion to equivalent linear simulation. If under ground structure was clear enough, Engineering (EB) and Seismic bedrocks (SB)

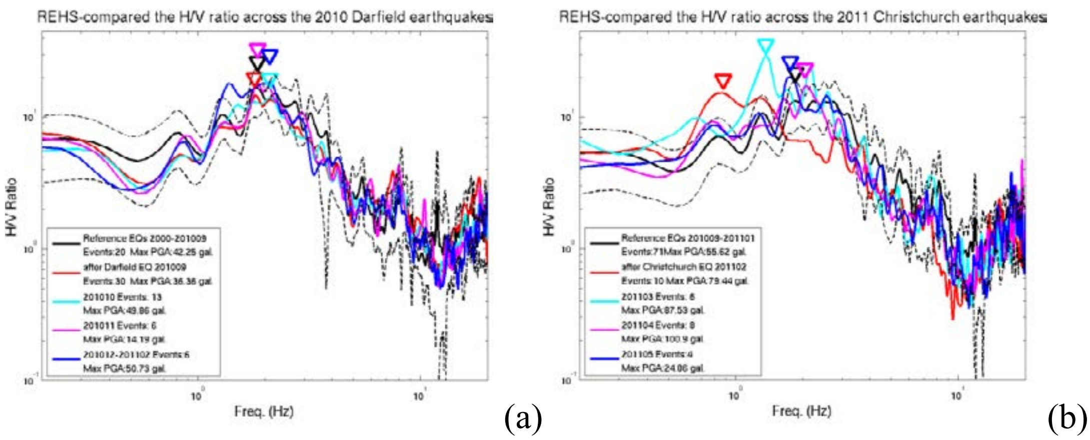

Fig. 7. HVSR of each time windows compared with different time span during 2011 Christchurch, New Zealand earthquake sequence. /

Рис. 7. HVSR каждого временного окна в сравнении с различным периодом времени в 2011 году в Крайстчерче, Новая Зеландия, последовательность землетрясений.

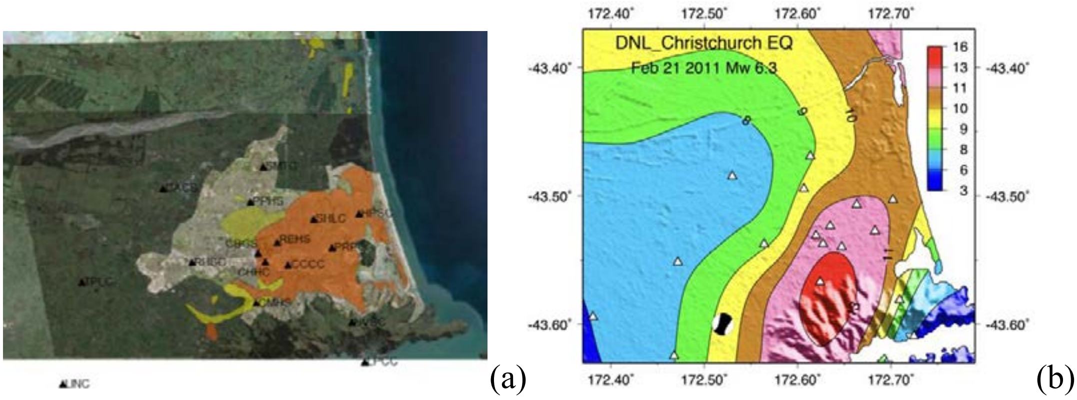

Fig. 8. (a) Liquefaction, (b) DNL distribution in the Christcurch area during the 2011 Christchurch, New Zealand earthquake [Wen et al., 2011b]. /

Рис. 8. (a) Разжижение, (b) Распределение DNL в районе Крайстчерч во время Крайстчерчского землетрясения 2011 года в Новой Зеландии [Wen et al., 2011b].

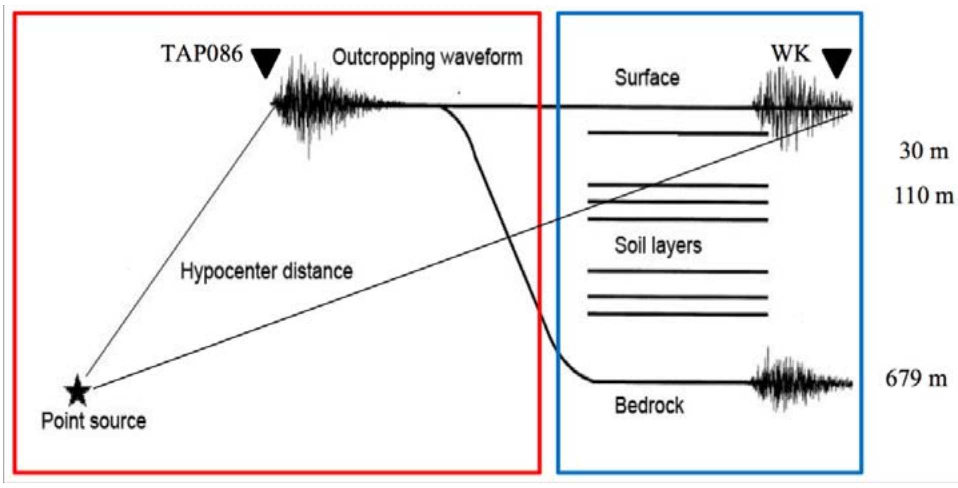

Fig. 9. Flowchart of combining equivalent linear method as a site correction for stochastic point source simulation technique [Saifuddin, 2013]. /

Рис. 9. Блок-схема объединения эквивалентного линейного метода в качестве коррекции площадки для способа моделирования стохастических точечных источников [Сайфуддин, 2013].

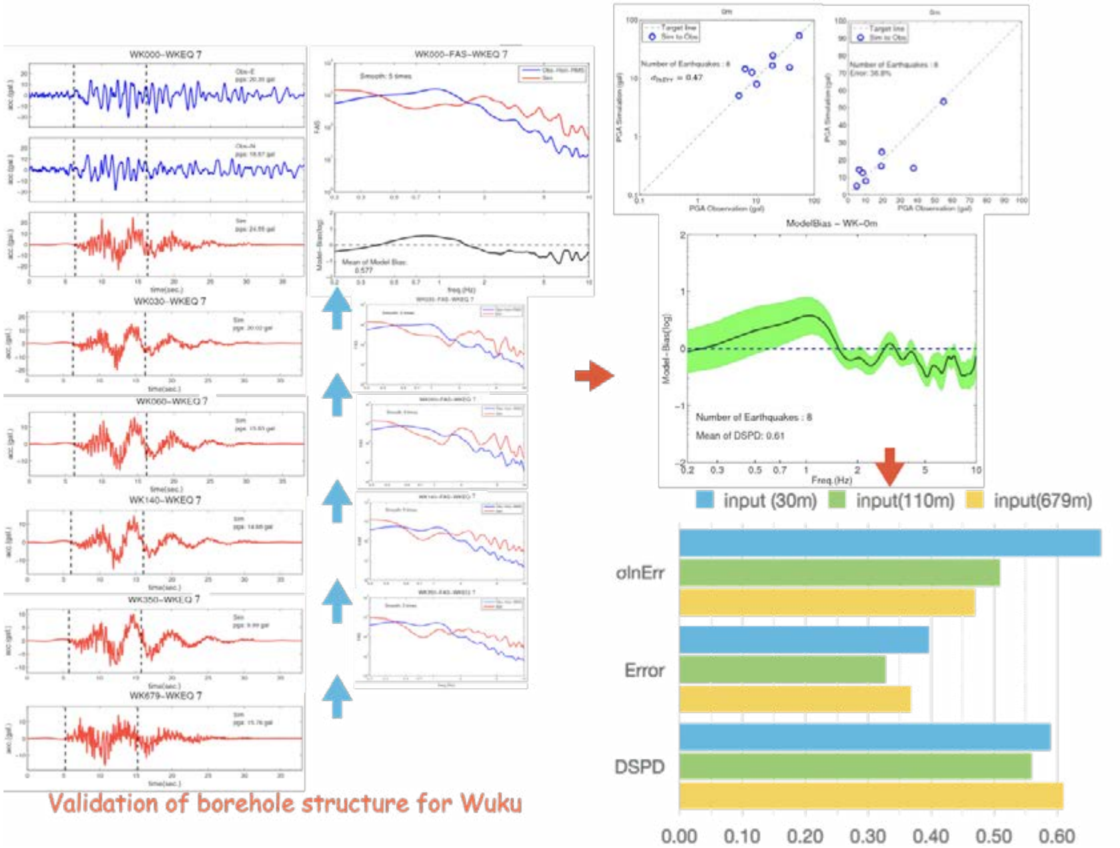

Fig. 10. Checking linear behavior while combing equivalent linear and stochastic simulation for seismic borehole array in Taipei, Taiwan (modified from [Saifuddin, 2013]). /
Рис. 10. Проверка линейного поведения при комбинировании эквивалентного линейного и стохастического моделирования для массива сейсмических скважин в Тайбэе, Тайвань (модифицировано из [Saifuddin, 2013]).

obtained similar result when applying equivalent linear method as site correction, from frequency and time domains shown that it was acceptable for using input motion in 30 meter and engineering bedrocks for small intensity events (as a linear site response, Fig. 10) and large intensity events (as nonlinear response, Fig. 11). It will be more useful in some sites where didn't have deep enough borehole structure. The applications will be more widely and save more budgets in many regions that people can drill more shallow boreholes in wider region rather than few deep boreholes.

3.1 Methodology
HVSR

One of the traditional site effect evaluation method were using spectral ratio between soil station and reference rock sites (could be surface or downhole stations). [Nakamura, 1989] found vertical FAS in surface soil site (S_V (f)) would be amplified comparing to downhole station (B_V (f)) while using downhole site as reference rock. The vertical amplification from source effect A_S (f) could be expressed as follows:

$$A_S(f) = \frac{S_V(f)}{B_V(f)}. \qquad (17)$$

Meanwhile, traditional soil to rock spectral ratio method could be written as S_E (f):

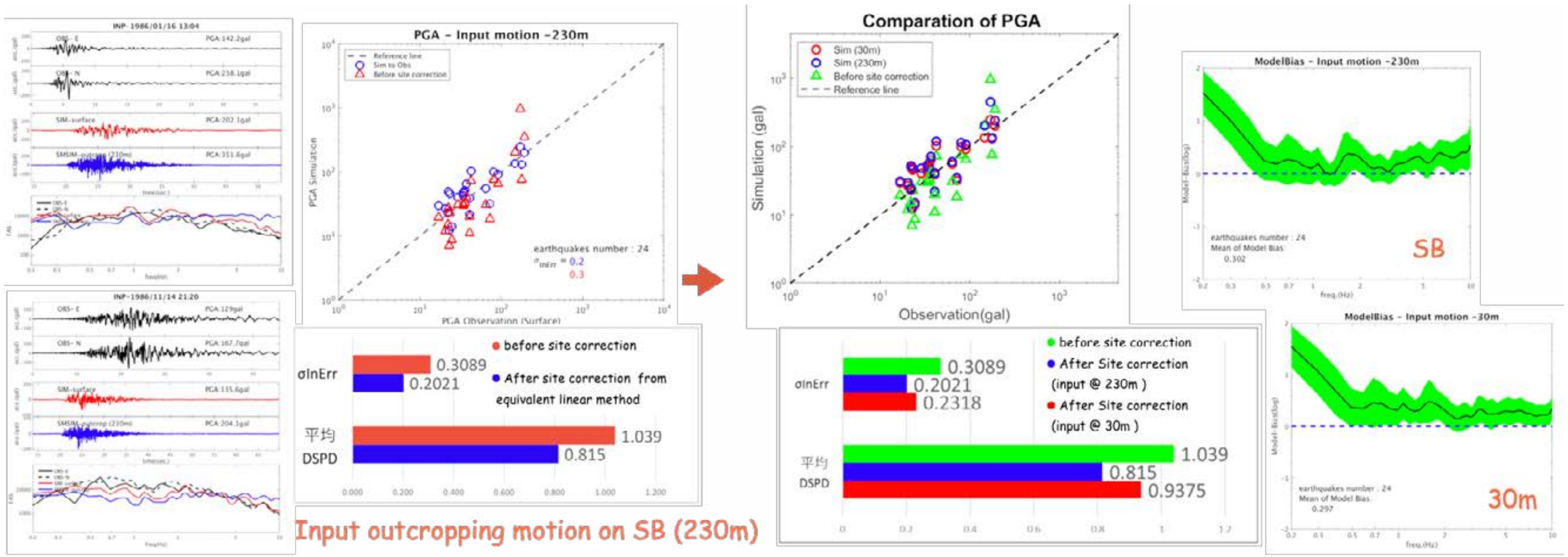

Fig. 11. Checking nonlinear behavior while combing equivalent linear and stochastic simulation for seismic borehole array in LSST, Taiwan (modified from [Lin, 2019]). /

Рис. 11. Проверка нелинейного поведения при комбинировании эквивалентного линейного и стохастического моделирования для массива сейсмических скважин в LSST, Тайвань (модифицировано из [Lin, 2019]).

$$S_E(f) = \frac{S_H(f)}{B_H(f)}. \tag{18}$$

Therefore, source related vertical amplification motion should be eliminated as

$$S_M(f) = \frac{S_E(f)}{A_S(f)} = \frac{\dfrac{S_H(f)}{B_H(f)}}{\dfrac{S_V(f)}{B_V(f)}} = \frac{\dfrac{S_H(f)}{S_V(f)}}{\dfrac{B_H(f)}{B_V(f)}} \tag{19}$$

Finally, Nakamura discovered the response for downhole reference site $\frac{B_H(f)}{B_V(f)}$ would be nearly equal 1 in site related frequency band. That means, the site amplification could be calculated from surface station directly as:

$$S_M(f) \approx \frac{S_H(f)}{S_V(f)}. \tag{20}$$

DNL

[Noguchi and Sasatani, 2008] hypothesized that the degree of nonlinearity of site response (DNL) depends on a summation of differences between H/V for strong motion and their reference. The DNL can be quantified by Eq. (21):

$$DNL = \sum \left| \log\left(\frac{R_{strong}}{R_{ref}} \right) \right| \cdot \Delta f \tag{21}$$

where R_{strong} means HVSR for strong motion and R_{ref} means HVSR for the reference (Weak motions). The DNL value shows a positive correlation with observed horizontal PGA/PGV when the soil condition is soft and fit the distribution of liquefaction region (Fig. 8, [Wen et al., 2011b]).

4 Results and discussion

The physical basis, methods and techniques for creation of seismic microzonation maps, including the use of modern high-power non-explosive sources (vibration and impulsive action) are considered. The physical formation mechanisms of algorithms of direct account of a number of soils indicators under heavy loads, which are the basis of relevant computer programs, are considered. It identifies changes or distortion of the amplitude-frequency characteristics of the original or the incoming wave field of seismic impact caused by the interaction of absorption and nonlinearity (or inelasticity) phenomena in different typical soils of the territory. The possibility of successful differentiation of soil conditions on the basis of the analysis of the relationship of the horizontal vibration spectrum of the initiated signal to the vertical spectrum and the predominant frequency of the ground motion is shown. The process of formation of seismic microzonation map of modern urban territory is considered.

In addition, soil nonlinearity researches indicated several convenient tools such as HVSR and DNL calculation could provide quantitatively account for nonlinear behavior during strong ground motions in Taiwan, New Zealand earthquakes. Synthetic Ground motions in both time domain (PGA) and frequency domain (FAS) of combining equivalent linear method and stochastic point source simulation technique indicated reasonable prediction level with observation records from seismic downhole arrays in Taiwan. It was noticeable that the simulation procedure has provided error level for user's choice while considering applications and budget consuming problems. Velocity and geology structures of drilling for top layer of 30 meter or engineering bedrocks might have acceptable predictions for efficiently widespread investigations.

References

1. Aguirre J., Irikura K. Nonlinearity, liquefaction, and velocity variation of soft soil layers in Port Island, Kobe, during the Hyogo-ken Nanbu earthquake. Bull. Seism. Soc. Am. 1997. 87. pp. 1244-1258.
2. Aubri D., Modaressi H. Calcul non lineaire des effects de site en genil paraseismigue. Meth. Elem. Finis. Proj. Geotech. Paris. 1987. pp. 239-247.
3. Bardet J.P., Tobita T. NERA, A computer program for Nonlinear Earthquake site Response Analyses of layered soil deposits. Univ. of Southern California, Los Angeles, 2001. 44 p.
4. Beresnev I.A., Wen K.L. Nonlinear ground response-A reality? (A Review). Bull. Seis. Soc. Am. 1996. 86 (6). pp. 1964-1978.
5. Beresnev I.A., Wen K.L., Yeh Y.T. Nonlinear soil amplification: Its corroboration in Taiwan. Bull. Seism. Soc. Am. 1995a. 85. pp. 496-515.
6. Beresnev I.A., Wen K.L., Yeh Y.T. Seismological evidence for nonlinear plastic ground behavior during large earthquakes. Soil. Dyn. Earthquake Eng. 1995b. 14. pp. 103-114.
7. Boore D.M., Seekins L., Joyner W.B. Peak acceleration from the 17 October 1989 Loma Prieta earthquake. Seismological Research Letter. 1989. 60. pp. 151-166.
8. Chandra J., Guéguen P., Bonilla L.F. PGA-PGV/Vs considered as a stress – strain proxy for predicting nonlinear soil response. Soil Dynamics and Earthquake Engineering. 2016. 85. pp. 146-160.
9. Darragh R.B., Shakal A.F. The site response of two rock and soil station pairs to strong and weak ground motion. Proc. 4th Intl. Conf. Seismic Zonation. 1991a. 3. pp. 359-366.
10. Darragh R.B., Shakal A.F. The site response of two rock and soil station pairs to strong and weak ground motion. Bull. Seism. Soc. Am. 1991b. 81. pp. 1885-1899.
11. Derras B., Bard P.Y., Régnier J., Cadet H. Non-linear modulation of site response: Sensitivity to various surface ground-motion intensity measures and site-condition proxies using a neural network approach. Engineering Geology. 2020. 269. (In press)
12. Guéguen P., Bonilla L.F., Douglas, J. Comparison of soil nonlinearity (In situ stress – strain relation and G=Gmax reduction) observed in strong-motion databases and modeled in ground-motion prediction equations. Bull. Seism. Soc. Am. 2019. 109 (1). pp. 178-186.
13. Huang J.Y., Wen K.L., Lin C.M., Kuo C.H., Chen C.T., Chang S.C. Site correction of a high-frequency strong-ground-motion simulation based on an empirical transfer function. J. Asian Earth Sci. 2017. 138. pp. 399-415.
14. Idriss I.M. Use of Vs30 to represent local site conditions. In Proceedings of the 4th IASPEI/IAEE international symposium. Proc. Esg4. 2011. Santa Barbara, USA.
15. Ishibashi I., Zhang. X. Unified dynamics shear module and damping ratios of sand and clay. Soils and foundations. 1993. 33 (1). pp. 181-191.
16. Kuo C.H., Huang J.Y., Lin C.M., Hsu T.Y., Chao S.H., Wen K.L. Strong ground motion and pulse-like velocity observations in the near-fault region of the 2018 Mw 6.4 Hualien, Taiwan, earthquake. Seismological Research Letters. 2019. 90 (1). pp. 40-50.
17. Lin C.Y. High frequency ground motion simulation with soil nonlinearity: a practice of LSST array. master thesis in National Central University. 2019. Taiwan, 83 p. (in Chinese with English abstract)
18. Nakamura Y. A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. QR of RTRI. 1989. 30 (1). pp. 25-33.
19. Nikolaev A.V. Seismic properties of a soft medium. Izv. of USSR Academy of Sciences Physics of Earth, 1967. №2. pp. 23-31.
20. Nikolaev A.V. Problems of nonlinear seismic. Moscow: Nauka. 1987. pp. 5-20. (in Russian)

21. Noguchi S., Sasatani T. Quantification of degree of nonlinear site response. The 14th World Conference on Earthquake Engineering. 2008. Beijing, China.

22. Noguchi S., Sasatani T. Nonlinear soil response and its effects on strong ground motions during the 2003 Miyagi-Oki intraslab earthquake. Earthquake. 2011. 63 (2), pp. 165-187. (in Japanese)

23. Ren Y. F., Wen R. Z., Yao X. X., Ji K. Five parameters for the evaluation of the soil nonlinearity during the Ms8.0 Wenchuan earthquake using the HVSR method. Earth, Planets and Space. 2017. 69:116.

24. Saifuddin. Stochastic ground motion simulation with site correction using equivalent-linear method. master thesis in National Central University, Taiwan. 2013. 126 p.

25. Schnabel P. B., Lysmer J., Seed H. B. SHAKE – a computer program for earthquake response analysis of horizontally layered sites. EERC, College of engineering, University of California, Berkeley. 1972.

26. Seed H. B., Romo M. P., Sun J. I., Jaime A., Lysmer J. The Mexico earthquake of September 19, 1985 – relationships between soil conditions and earthquake ground motion // Earthquake Spectra. 1988. 4. pp. 687-789.

27. Studer J. A., Ziegler A. The geotechnical aspect of microsonation. Proceedings of the 8-th European Conference on Earthquake Engineering. 1986. 2. pp. 9-16.

28. Wen K. L. Non-linear soil response in ground motions. Earthq. Eng. Struct. Dyn. 1994. 23. pp. 599-608.

29. Wen K. L., Beresnev I. A., Yeh Y. T. Non-linear soil amplification inferred from downhole strong seismic motion data. Geophysical Research Letters. 1994. 21. pp. 2625-2628.

30. Wen K. L., Beresnev I. A., and Yeh Y. T. Investigation of non-linear site amplication at two downhole strong ground motion arrays in Taiwan. Earthq. Eng. Struct. Dyn. 1995. 24. pp. 313-324.

31. Wen K. L., Chang T. M., Lin C. M., Chiang H. J. Identification of nonlinear site response using the H/V spectral ratio method. Terrestrial atmospheric & oceanic sciences. Sci. 2006. 17 (3). pp. 533-546.

32. Wen K. L., Huang J. Y., Li X. J., Zhou Z. H., Wen R. Z. Nonlinear site response of the 2008 Wenchuan, China earthquake from time-frequency analysis. Proc. 8CUEE. 2011a. P121, Tokyo, Japan.

33. Wen K. L., Huang J. Y., Chen C. T., Cheng Y. W. Nonlinear site response of the 2010 Darfield, New Zealand earthquake sequence. Proc. Esg4. 2011b. Santa Barbara, USA.

34. Zaalishvili V. B. The weighted average period of soil vibrations excited by various kinds of artificial sources. Abstracts of the Joint session of the Research Institute of the Transcaucasian Republics on Construction: Mecniereba. Tbilisi. 1987. 350 p. (in Russian).

35. Zaalishvili V. B. Seismic microzonation based on the study of nonlinear soil properties by artificial sources. Abstract of the dissertation on the doctor of physical and mathematical sciences. 1996. Moscow State University. Moscow. 43 p.

36. Zaalishvili V. B. Physical basics of seismic microzonation. Moscow. UIPE RAS. 2000. 367 p. (in Russ.)

37. Zaalishvili V. B., Otinashvili M. G. Analysis of ground strong motions by means of numerical methods. Theory of constructions and earthquake engineering. 2000. Tbilisi. ISMIS AS of Georgia. 1. pp. 67-71. (in Georgian)

38. Zaalishvili V. B. Seismic microzonation of urban territories, settlements and large building sites. Moscow. Nauka. 2009. 350 p. (in Russ.).

39. Zaalishvili V. B. Assessment of seismic hazard territory. Earthquake Engineering. Published by InTech. Edited Halil Sezen. 2012. pp. 25-64.