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Mechanisms and Control of Accumulated Plastic Deformation in Highway Subgrades for Durable Service

Saiyu Ni[1,a]**, Dingyu Ni**[2,b,*]
[1]Wenzhou Design Assembly Company Ltd., Wenzhou 325000, China
[2]Wenzhou Polytechnic, Wenzhou, China
Email: [a]nisaiyu_wzda@163.com. [b,*]Corresponding author: 2021000126@wzpt.edu.cn

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Abstract

Under long-term cyclic traffic loading, subgrade soils may develop accumulated irrecoverable plastic strain, which gradually evolves into permanent deformation affecting pavement smoothness, bearing capacity, and durability. Compared with construction-stage compaction quality, permanent deformation of subgrades during operation can better reflect the long-term service risks of road structures under coupled loading–environmental effects. This paper systematically reviews the testing and characterization, influencing factors, prediction models, structural calculation methods, and control approaches for subgrade permanent deformation. The results indicate that water content, degree of compaction, cyclic stress, confining pressure, loading duration, rest period, and overburden static load jointly govern the development of permanent deformation. Existing constitutive models have a solid theoretical basis but are limited by computational efficiency in long-term cyclic analysis, whereas mechanical–empirical models are convenient for engineering applications but still face limitations in parameter calibration and generalization capability. Future research should strengthen the reproduction of service conditions, coupled moisture-field and stress-field analysis, and reliability-based control criteria, thereby providing a basis for durable subgrade design and maintenance decision-making.

Keywords

Highway subgrade; Long-term cyclic loading; Permanent deformation; Prediction model; Durable subgrade

1. Introduction

As highway construction in China gradually shifts from large-scale expansion to existing-network maintenance and quality enhancement, increasing attention has been paid to the long-term service performance of road structures. Although pavement distresses such as cracking, rutting, and settlement are first manifested in the surface layer, their formation is often associated with long-term deformation, strength degradation, and fluctuations in the moisture state within the subgrade [1–3]. Located between the pavement structure and the foundation, the subgrade is a key load-bearing unit responsible for the transmission, diffusion, and redistribution of traffic loads, and its stability directly determines the overall durability of road structures. Compared with the visible nature of pavement distresses, subgrade distresses are concealed, progressive, and cumulative. They are difficult to identify at an early stage; once they propagate to the pavement structural layers, substantial maintenance costs and traffic impacts are often incurred.During subgrade service, vehicle loads are characterized by high frequency, repetition, and randomness. Under long-term cyclic loading, subgrade soils undergo small plastic deformation in each loading cycle. Although the deformation induced by a single loading cycle is limited, its cumulative effect under millions or even tens of millions of traffic load repetitions may lead to significant permanent deformation [1,2]. Unlike elastic rebound deformation, this type of deformation cannot be fully recovered after unloading. It may increase additional tensile stress and tensile strain in the pavement structure, thereby inducing pavement cracking, rutting, and differential settlement. Permanent deformation of subgrades has become one of the key factors affecting the design and durability evaluation of long-life road structures [1,4].

In current subgrade design and construction control, indicators such as degree of compaction, optimum water content, resilient modulus, and deflection are commonly used to evaluate construction quality or the bearing state of pavement structures. These indicators play important roles in construction acceptance and structural design; however, they are insufficient for reflecting the accumulation of plastic strain caused by long-term cyclic loading. This limitation is particularly evident in humid, rainy, freeze–thaw-prone regions or areas with significant groundwater level fluctuations, where the moisture content and compaction state of subgrades evolve over time, resulting in a clear discrepancy between the initial construction state and the long-term service state [3,6,8]. Therefore, relying solely on construction-stage compaction indicators and elastic response indicators makes it difficult to accurately evaluate the risk of permanent deformation in subgrades during operation. Accordingly, it is necessary to develop a comprehensive understanding of permanent deformation in highway subgrades from the perspectives of material testing, influencing mechanisms, prediction models, and engineering control.

2. Testing Methods and Parameter Settings for Subgrade Permanent Deformation

Subgrade permanent deformation generally refers to the accumulation of irrecoverable plastic strain in subgrade soils under long-term cyclic loading. Compared with instantaneous elastic deformation, permanent deformation cannot be fully recovered after unloading; instead, it accumulates with increasing loading cycles and gradually manifests as subgrade settlement, pavement rutting, structural cracking, and differential deformation [1,2,5]. Subgrade permanent deformation is not only a result of the dynamic response of soils, but also an important indicator for evaluating the long-term service performance of roads. Its development is characterized by accumulation, path dependence, and state dependence. It is controlled by internal factors such as soil type, degree of compaction, water content, and structural state, while also being closely related to external conditions such as confining pressure, cyclic stress amplitude, loading frequency, loading duration, rest period, and initial consolidation condition [1,9,10].

At present, the dynamic triaxial test remains the most commonly used laboratory method for investigating the permanent deformation of subgrade soils. Under relatively controlled conditions, this method can simulate the three-dimensional stress state of a subgrade soil element. Specifically, confining pressure is used to simulate the lateral restraint acting on the subgrade soil, while vertical cyclic deviator stress is used to simulate the repeated action of vehicle loads. Under a given initial consolidation condition, the accumulation of plastic strain with the number of loading cycles can then be recorded [1,2,10]. Existing studies generally classify the test conditions for subgrade permanent deformation into four categories: physical state, stress level, loading characteristics, and loading mode. The physical state includes water content, degree of compaction, wetting－drying cycles, freeze－thaw cycles, and soil type; the stress level includes confining pressure and cyclic stress amplitude; the loading characteristics include load waveform, frequency, loading duration, and rest period; and the loading mode involves moving traffic loads, overburden static load, contact stress, and consolidation conditions [1,4,9].

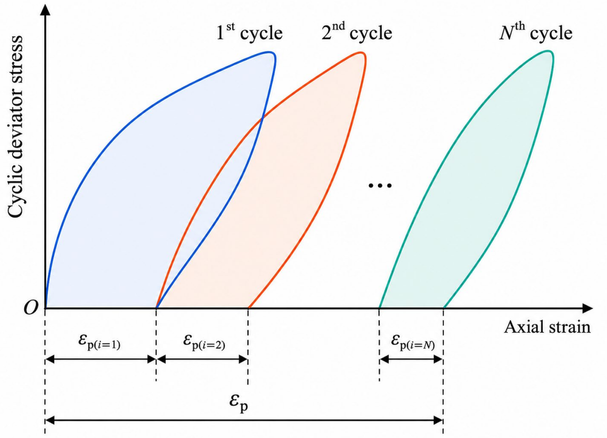

Figure 1. Schematic Diagram of Permanent Deformation of Subgrade Soil.

From the perspective of physical state, water content and degree of compaction are fundamental variables affecting the results of permanent deformation tests. During subgrade construction, the optimum water content and specified degree of compaction are commonly adopted as quality control targets. However, during actual operation, the moisture state of the subgrade gradually changes under the combined effects of rainfall infiltration, groundwater level fluctuation, capillary rise, evaporation, and pavement-covering effects [2,3,8]. In humid regions in particular, the long-term moisture condition of the subgrade may gradually evolve from the optimum water content during construction to an equilibrium moisture state, resulting in reduced soil suction, weakened interparticle bonding, and decreased resistance to deformation [2,3]. Meanwhile, the degree of compaction is not constant; the compacted fill may undergo densification adjustment or local loosening under long-term loading and moisture migration. Therefore, permanent deformation tests should not be conducted only under a single construction-stage water content or compaction degree. Instead, different water contents, degrees of compaction, and environmental paths such as wetting–drying and freeze–thaw cycles should be considered according to the regional moisture environment and service conditions, so as to reveal the accumulation characteristics of plastic strain in subgrade soils during state evolution [4,6].

From the perspective of stress level, the permanent deformation of subgrade soil exhibits significant stress dependence. After vehicle loads are transmitted downward through the pavement structure, a dynamic stress field that attenuates with depth is formed within the subgrade. At the same time, the self-weight of the pavement structure and overlying fill keeps the subgrade soil under a certain static stress state for a long period. Therefore, the confining pressure and cyclic stress amplitude adopted in laboratory tests should, as far as possible, cover the actual stress range experienced by subgrade soil elements in the field. If the cyclic stress is set too low, the measured permanent deformation may be underestimated and may fail to reflect cumulative damage under heavy traffic. Conversely, if the cyclic stress is set too high, the specimen may enter a failure state prematurely, deviating from the progressive deformation characteristics under normal service conditions [1,9].

From the perspective of loading characteristics, field vehicle loads are highly random and moving in nature, rather than ideal single-period cyclic loads. Vehicle type, axle load, travelling speed, tire–road contact condition, pavement smoothness, and structural layer configuration all affect the magnitude, duration, and rest period of the dynamic stress acting on subgrade soils. In laboratory dynamic triaxial tests, a haversine waveform is commonly used to simulate vehicle-induced dynamic loading. This is a simplified representation of traffic loading and can reasonably reflect the basic “loading–unloading–rest” characteristics of vehicle loads. However, this simplification also has limitations. Actual traffic loads are not perfectly regular repeated loads, and both load amplitude and time interval exhibit random fluctuations. Moreover, the loading duration and rest period at different vehicle speeds are not simply linearly scaled, and the viscoelastic–plastic response of soils may cause the effect of loading frequency on permanent deformation to become nonlinear [1,10]. Therefore, in test design, attention should be paid not only to loading frequency but also to the effects of single-load duration and rest period on permanent deformation accumulation, so as to avoid replacing the actual traffic loading process merely with a frequency parameter [7,10].

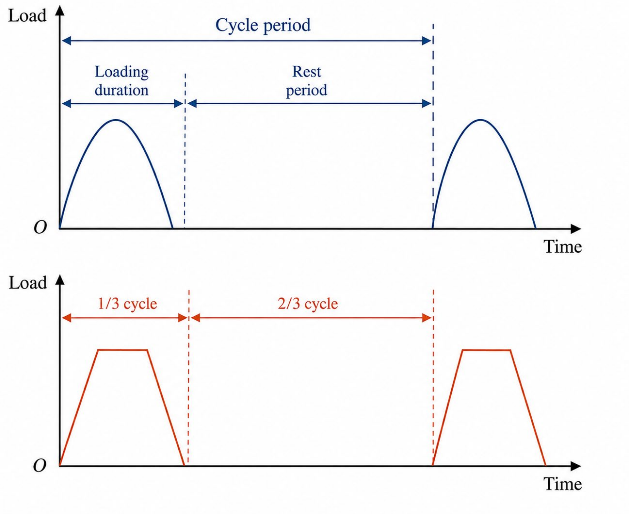

Figure 2. The setting method of highway traffic load.

Loading mode is one of the most easily simplified yet highly critical aspects of permanent deformation testing. During service, a subgrade soil element is not subjected to vehicle-induced dynamic loading alone; rather, its deformation occurs under the combined action of lateral confining pressure, overburden static load, and cyclic dynamic loading. Among these factors, confining pressure represents the lateral restraint imposed by the surrounding soil, the overburden static load originates from the self-weight of the pavement structure and overlying fill, and the cyclic deviator stress mainly corresponds to the additional dynamic stress induced by vehicle loading. If only confining pressure and cyclic deviator stress are applied in the test while the overburden static load and initial consolidation process are neglected, the obtained results can hardly reflect the stress history formed in the subgrade soil before operation [1,9]. Existing studies have indicated that the combination of static and dynamic loads, as well as their loading sequence, can influence the subsequent development of dynamic deformation in specimens. At present, the settings of contact stress, consolidation duration, and consolidation termination criteria are still not fully consistent among different studies, which is also one of the important reasons for the limited comparability of permanent deformation test results [1,3].

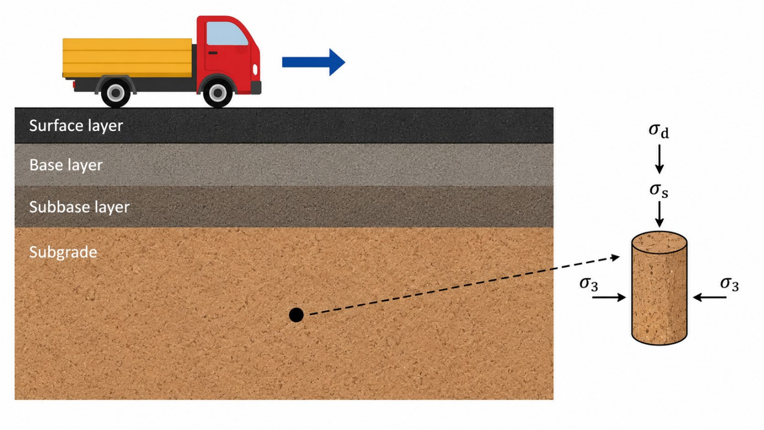

Figure 3. Typical stress state of a highway subgrade soil element.

3. Main Factors Influencing Permanent Deformation of Subgrades

Permanent deformation of subgrades is primarily controlled by water content and degree of compaction. An increase in water content reduces the matric suction of unsaturated soil, weakens interparticle adsorption and structural strength, and makes the soil more prone to plastic flow and accumulated deformation [2,3,8]. This is particularly evident in humid and hot regions of southern China, where the water content of subgrades may gradually evolve from the optimum water content during construction to an equilibrium moisture content during long-term service, and may even approach the plastic-limit water content in some sections. Under such conditions, both the shear strength and resilient modulus of subgrade soil decrease, while the growth rate of permanent deformation increases significantly [2,8]. Increasing the degree of compaction can generally reduce porosity, enhance interparticle interlocking and skeleton stability, and thus inhibit the development of permanent deformation. However, when the subgrade undergoes wetting, fine-particle migration, or structural relaxation during operation, the high-compaction state formed during construction may not be maintained over the long term [1,4].

Environmental cycling further amplifies the risk of permanent deformation. Wetting – drying cycles can induce repeated changes in soil suction, microcrack development, and structural softening, resulting in evident cyclic accumulation of permanent deformation [4]. Freeze – thaw cycles can alter the soil structure through ice crystal growth, thawing-induced drainage, and pore reconstruction, making freeze – thaw-affected soils more susceptible to plastic strain under cyclic loading [6]. For special soils such as saline soil, expansive soil, peat soil, and lateritic clay, environmental sensitivity is stronger, and changes in water content, temperature, and chemical environment may lead to abrupt changes in the development pattern of permanent deformation.

Stress level is another key factor governing the development mode of permanent deformation. In general, the greater the cyclic stress amplitude, the larger the plastic strain generated in each loading cycle and the faster the accumulation of permanent deformation. An increase in confining pressure can enhance lateral restraint and suppress the development of shear and volumetric deformation [1,5,9]. In actual subgrades, the dynamic stress induced by traffic loading attenuates with depth, making the upper part of the subgrade the most sensitive zone for permanent deformation. However, when the groundwater level rises, the water content increases, or drainage in the subgrade structure is poor, significant deformation may also occur at greater depths due to a reduction in effective stress [2,3].

Loading characteristics also affect the development of permanent deformation. Changes in vehicle speed alter the loading duration and rest period; heavy traffic increases the cyclic stress amplitude; and channelized traffic causes loading to be concentrated beneath wheel paths over long periods. A longer loading duration generally increases soil plastic deformation, whereas an appropriate rest period is conducive to the dissipation of pore water pressure and deformation recovery [1,10]. The effect of loading frequency is not entirely consistent among different soil types, as it is jointly governed by the viscoelastic - plastic characteristics of soil, drainage conditions, and stress level [7,9]. Therefore, studies on subgrade permanent deformation should not use frequency alone as a substitute for the actual traffic loading process, but should instead focus on the relationships among loading duration, rest period, and the internal response of soil.

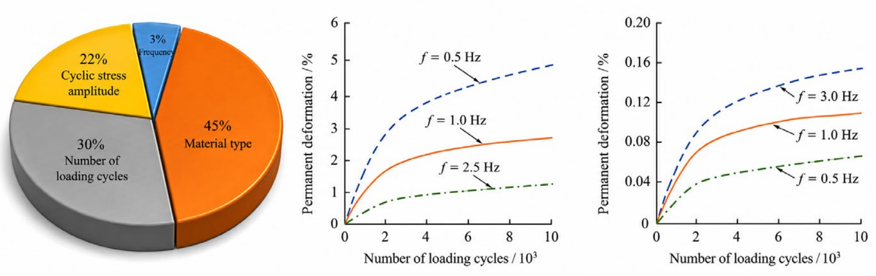

Figure 4. Representative results of permanent deformation of highway subgrade soil at different frequencies.

Loading mode and initial stress state affect the comparability of test results. The settings of overburden static load, contact stress, and consolidation duration vary among different studies, resulting in discrepancies among experimental data. In the field, subgrade soils are simultaneously subjected to vertical self-weight stress, lateral restraint, and vehicle-induced dynamic loading. Their coefficient of earth pressure at rest, consolidation state, and stress history all influence the development of permanent deformation [1,9]. Establishing more reasonable methods for determining the initial stress state according to different soil types would help improve the accuracy of laboratory tests in simulating engineering conditions.

4. Prediction Models for Subgrade Permanent Deformation

To support subgrade structural design and long-term performance evaluation, researchers have proposed various prediction models for permanent deformation. In general, these models can be classified into dynamic constitutive models based on classical soil mechanics theory and mechanical – empirical models based on experimental observations. The former emphasize the stress – strain relationship of materials as well as yielding, hardening, and plastic strain accumulation mechanisms during cyclic loading, and therefore have strong theoretical interpretability. The latter usually establish functional relationships between permanent strain and factors such as the number of loading cycles, stress state, water content, and degree of compaction based on test curves, and are characterized by simple forms and convenient engineering application [1,2,5].

Constitutive models based on classical soil mechanics commonly employ theoretical frameworks such as multi-yield surface theory, bounding surface theory, kinematic hardening, or the modified Cam-clay model to describe cyclic plastic behavior of soils. These models can describe hysteresis loops, stress paths, and strain responses under a single or a small number of cyclic loads in relatively great detail, and are suitable for revealing soil deformation mechanisms. However, in road engineering, subgrades are subjected to a very large number of load repetitions. If the stress – strain path of each cycle is tracked individually, the computational cost increases dramatically. For long-term prediction at the scale of actual subgrade structures, complex constitutive models often face difficulties such as parameter acquisition, low computational efficiency, and insufficient convergence stability [7,10].

Mechanical – empirical models are more widely used in road engineering. Early models often used logarithmic or power functions of the number of loading cycles to describe the growth of permanent deformation, which can effectively capture the basic feature that the deformation curve gradually slows with increasing load repetitions. With further research, variables such as stress level, mean bulk stress, octahedral shear stress, degree of saturation, matric suction, dry density ratio, and material composition have been gradually incorporated into these models to improve their adaptability to different conditions [2,5,10]. Such models can achieve a balance between computational efficiency and prediction accuracy and are suitable for use in structural calculation methods such as the layerwise summation method.

In recent years, data-driven models have also been increasingly applied to permanent deformation prediction. Deep learning methods can extract nonlinear relationships from multi-factor experimental data and are particularly suitable for predicting complex deformation under the combined effects of freeze – thaw cycles, water-content variation, and cyclic loading [6]. However, such methods still rely on high-quality experimental databases, and the interpretability and cross-regional applicability of their prediction results require further improvement.

Although mechanical–empirical models are convenient for engineering application, they still have three main limitations. First, model parameters are often calibrated based on specific soil samples and test conditions, which may lead to large errors when applied across regions or soil types. Second, the model form usually presupposes the evolution pattern of the permanent deformation curve, making it difficult to uniformly describe different development modes such as plastic shakedown, plastic creep, and incremental collapse. Third, under multi-factor coupling, correlations may exist among model parameters, resulting in insufficiently clear physical meanings [5,7]. Future model development should further strengthen the mechanistic interpretation of material state, stress path, and environmental cycling while maintaining engineering simplicity.

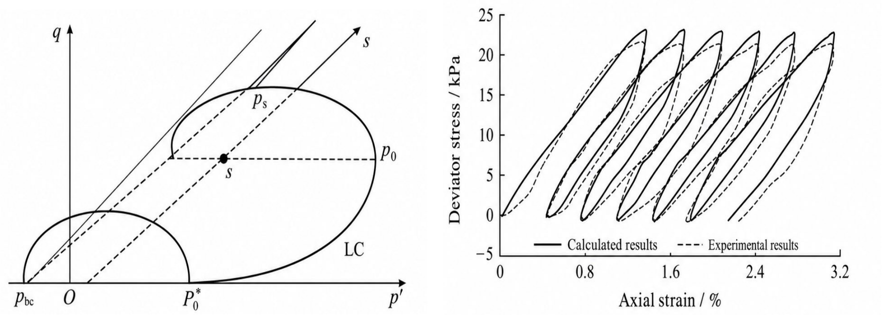

Figure 5. Application of dynamic constitutive models based on classical soil mechanics.

5. Conclusions

Permanent deformation of subgrades under long-term cyclic loading is the result of the combined effects of material state, traffic loading, environmental actions, and structural response. Existing studies have developed a relatively systematic technical framework involving dynamic triaxial testing, influencing-factor analysis, empirical models, constitutive models, and data-driven prediction methods [1,2,5,7]. However, several problems remain in engineering application, including inconsistent test parameter settings, insufficient simulation of long-term service conditions, inadequate understanding of moisture–stress coupling mechanisms, and control criteria that are overly focused on material indices.

Future research should be advanced collaboratively in terms of element testing, structural calculation, field monitoring, and standard systems. In testing, field stress monitoring, vehicle load spectra, and regional hydrological environments should be incorporated to establish dynamic triaxial test methods that more closely represent service conditions. In modeling, stronger links should be established between state parameters—such as water content, degree of saturation, suction, degree of compaction, and gradation—and the parameters of permanent deformation models. At the structural level, control criteria for subgrade permanent deformation should be clarified according to traffic grade, climatic zone, and fill material type [4,6,8].

Only by extending permanent deformation control to the entire process of design, construction, and maintenance can the long-term stability of highway subgrades and the durability of road structures be effectively improved.

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References

[1] Zhang J., Zhang A., Li J., Fan H. Enhanced understanding on permanent deformation behaviour of subgrade compacted clay under long-term cyclic loading[J]. Soil Dynamics and Earthquake Engineering, 2024, 187: 108972. DOI: 10.1016/j.soildyn.2024.108972.

[2] Chu X., Dawson A., Thom N., Chen H., Qin L. Permanent deformation characteristics of unsaturated subgrade soils under cyclic loading[J]. Case Studies in Construction Materials, 2024, 20: e03099. DOI: 10.1016/j.cscm.2024.e03099.

[3] Everton J. H. C., Erlingsson S. Characterising the permanent deformation of subgrade soils under seasonal variation[J]. Canadian Journal of Civil Engineering, 2024, 52(3): 317 – 333. DOI: 10.1139/cjce-2024-0077.

[4] Wang K., Qiu Z., Hu H., Sun M., Wang J. Macro-meso mechanical behavior and degradation mechanisms of silty clay subgrade subjected to coupled traffic loading and dry-wet cycles[J]. Transportation Geotechnics, 2025, 55: 101725. DOI: 10.1016/j.trgeo.2025.101725.

[5] Li C., Zhang C., Weng H., Qin Y., Shang H., Zhang J. Study on permanent deformation properties of construction waste soil under traffic loading[J]. Frontiers in Materials, 2025, 12: 1621109. DOI: 10.3389/fmats.2025.1621109.

[6] Liu X., Li J., Liu J., Huang C., Liu L. Prediction of permanent deformation of subgrade soils under F-T cycles using SABO-optimized CNN-BiLSTM network[J]. Case Studies in Construction Materials, 2024, 21: e03807. DOI: 10.1016/j.cscm.2024.e03807.

[7] Lees A., Tutumluer E. Characterising geomaterial shakedown and related deformation accumulation from cyclic triaxial tests[J]. Transportation Geotechnics, 2025, 50: 101455. DOI: 10.1016/j.trgeo.2024.101455.

[8] Rahman M. M., Gassman S. L., Islam K. M. Effect of moisture content on subgrade soils resilient modulus for predicting pavement rutting[J]. Geosciences, 2023, 13(4): 103. DOI: 10.3390/geosciences13040103.

[9] Singh A. K., Sahoo J. P. Undrained cyclic loading response of subgrade soil subjected to varying moisture content and stress level[J]. International Journal of Geomechanics, 2023, 23(2): 04022284. DOI: 10.1061/IJGNAI.GMENG-6536.

[10] Li Y., Nie R., Yue Z., Leng W., Guo Y. Dynamic behaviors of fine-grained subgrade soil under single-stage and multi-stage intermittent cyclic loading: Permanent deformation and its prediction model[J]. Soil Dynamics and Earthquake Engineering, 2021, 142: 106548. DOI: 10.1016/j.soildyn.2020.106548.