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Surface-mounted bender elements for measuring horizontal shear wave velocity of soils*

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Abstract: The bender element testing features its in-plane directivity, which allows using bender elements to measure the shear wave velocities in a wider range of in-plane configurations besides the standard tip-to-tip alignment. This paper proposed a novel bender element testing technique for measuring the horizontal shear wave velocity of soils, where the bender elements are surface-mounted and the axes of the source and receiver elements are parallel to each other. The preliminary tests performed on model ground of silica sand showed that, by properly determining the travel distance and time of the shear waves, the surface-mounted bender elements can perform as accurately as the conventional "tip-to-tip" configuration. Potentially, the present system provides a promising nondestructive tool for characterizing geomaterials and site conditions both in laboratory and in the fields.

Key words: Bender elements, Shear wave velocity, Model test, Nondestructive evaluation, Surface-mounted, Sand
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INTRODUCTION

New demands in soil mechanics research and geotechnical engineering practice require advanced characterization techniques in both laboratory and the field for monitoring processes and assessing various conditions, especially for those assessments involving sample disturbance (Sasitharan *et al*., 1994), the processes monitoring catastrophe (Lee and Santamarina, 2006), and the quality control of soil improvement (Arulrajah *et al*., 2006).

Previous studies show that strong interrelation exists between the shear wave velocity and many other factors dominating soil behavior (Lee and Huang, 2007). Therefore shear wave-based measurement offers geotechnical engineers the unique opportunities in characterizing sites, materials and processes (Santamarina *et al.*, 2001; Zhou and Chen, 2005). Compared with other methods, the piezoelectric bender element technique is a relatively simple and convenient nondestructive method of determining shear wave velocities in laboratory samples prior to destructive loadings (Brignoli *et al*., 1996; Lee and Santamarina, 2005; Zhou *et al*., 2005a; Zhou and Chen, 2007). In a bender element test system, with two piezoelectric benders as a transmitter and a receiver, the shear waves can be produced, propagated and detected. The determination of shear velocity V_s is a straightforward matter of dividing the travel distance L between the elements (tip-to-tip) by the travel time t of the shear wave, as

$$V_s=L/t. \tag{1}$$

Although the bender element technique is well developed in laboratory (Kuwano and Jardine, 2002; Yamashita *et al*., 2007), the confined condition and

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conventional "tip-to-tip" arrangement limit its further applications. Recently, some researchers turn to the flexible arrangements of the bender elements for high-quality measurements under different conditions, such as the horizontally mounted elements (Pennington *et al.*, 2001), the side-mounted bender elements (Clayton *et al.*, 2004), and the shear wave velocity measurements both in laboratory and in the fields (Landon *et al.*, 2007).

The work described in this paper aims to extend the applicability of the bender element technique to the conditions other than that in the triaxial apparatus. A novel technique using the surface-mounted bender elements was proposed for measuring the horizontal shear wave velocity of soil surfaces in laboratory or in the fields. The feasibility and accuracy of this technique were validated by its comparison with conventional "tip-to-tip" measurements in model ground of silica sand No. 8.

SURFACE-MOUNTED BENDER ELEMENTS

Feasibility of parallel axes configuration

Practices in bender element testing revealed the in-plane directivity of sources and receivers (Sawangsuriya *et al.*, 2006). Lee and Santamarina (2005) explored the in-plane directivity of bender elements, and the test results showed that in the parallel axes configuration, the amplitude at 90° is about 50% of the amplitude at 0°, which suggested the potential use of bender elements in a wider range of the in-plane configurations. Recently, Asaka *et al.*(2007) developed a nondestructive technique to inspect the strength of cement-treated ground by measuring surface shear wave velocity in the field and in the laboratory. On the other hand, Ziv (2003a; 2003b) studied the response of an elastic half-space under a momentary shear line impulse based on the characteristics theory in conjunction with kinematical relations, which explicitly revealed that the shear waves would propagate along the shallow depth near the surface of a half-space.

Therefore, if the bender elements could be parallel arrayed and mounted on the soil surface, they will allow the propagation of S_{hh}-waves (horizontal propagation shear waves with soil particles vibrating in horizontal direction) (Fig.1). Then the horizontal shear wave velocity (V_{sh}) at surface of soil samples or ground could be determined and correlated to the required soil indexes such as shear strength (Cha and Cho, 2007), which would result in a new non-destructive evaluation method.

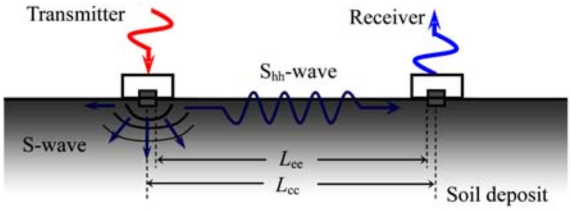


Fig.1 Illustration of surface-mounted bender elements for V_s measurement

Design of bender element system

To meet the requirements of possible applications such as soil sample disturbance assessment or quality control of soil improvement, the surface-mounted bender elements should be capable of measuring different types of soils (from soft clay to stiff cement-treated ground) and have adjustable measuring distances during testing. This requires the flexible resonant frequency and energy transmission ability of bender elements, which can be satisfied by adjusting penetrating length and the geometries of bender element patches.

The types of bender element used in the present system are Q215-A4-303Y (transmitter) and Q215-A4-303X (receiver), produced by Piezo System Inc., USA, with dimensions of 31.8 mm×12.7 mm×0.38 mm (length×width×thickness). Electrical insulation and waterproofing of the transducers are obtained by applying an even layer of epoxy resin. As shown in Fig.2, the transmitter or receiver consists of two separate parts: the core element and the outer cap. The core element is made of one piezoelectric patch and a small-size plastic clamp, therefore it is light and suitable for V_s measurement on soil samples in laboratory as long as it is sufficiently fixed. By inserting the core element into the outer cap and adjusting the penetrating length, the bender elements can be mounted on large-size soil surface (e.g., model ground or the fields).

The bender element test setup is similar to those in previous studies (Zhou *et al.*, 2005b; Chen and Zhou, 2006), which includes a function generator (Tektronix AFG310 Arbitrary Function Generator), a power amplifier (EPA-104-230 Piezo Linear Amplifier) for the applied voltage and a signal amplifier for the receiving signal, and an oscilloscope (Tektronix TDS3032 Digital Phosphor Oscilloscope) for collecting transmitting and receiving signals. During testing, the signal stacking is used to improve the quality of the receiving signal.

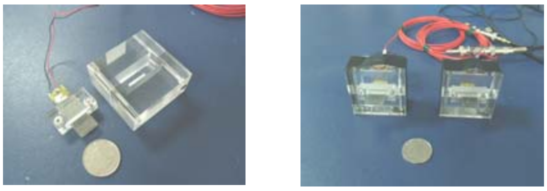

(a) (b)

Fig.2 (a) A core element and a outer cap; (b) An assembly in fixed mode

COMPARISON TESTS IN MODEL GROUND

Since the “source to receiver” arrangement in surface-mounted bender elements is the type of “side-to-side” but not the conventional “tip-to-tip”, the determination of the travel distance of shear waves should be cautiously checked. As shown in Fig.1, whether the travel distance is “center-to-center” (L_{cc}) or “edge-to-edge” (L_{ee}) is in question, because the width of piezoelectric element should not be neglected in short distance measurement.

To address these problems, a model test is designed for comparing two types of measuring arrangements. The test material is silica sand No. 8 (poorly graded, subangular, fine-grained silica containing 49% of non-plastic fines), whose physical properties are G_s=2.645, e_{max}=1.381, e_{min}=0.721, D_{10}=0.03 mm, D_{50}=0.073 mm, and C_u=2.88.

The model ground is prepared by the air-pluviation method in a laminar box. The inside dimensions of the model container are 80 cm long, 35 cm wide and 40 cm deep. The soil thickness of the model was 30 cm. After saturation via vacuum method, the model was rotated at 30 g centrifugal acceleration for 1 h and then drained. The water content before measurements is w=15%, and the final relative density is D_r=87%. Two bender elements were embedded under the model surface in the conventional “tip-to-tip” pattern (L_{tt}=40 cm) for comparison purpose.

The test arrangements are illustrated in Fig.3. Because V_s is mainly dominated by soil fabric and stress condition, the key issue of proper comparison is to insure that both tests are conducted under the same stress condition, given that model ground is uniformly prepared. As the penetrating depth of surface-mounted bender element is about 10 mm, the part of sand above the conventional “tip-to-tip” type should be removed so that the benders may vibrate at almost the same depth. To minimize the soil disturbance effects, tests were arranged in two steps: firstly, two parallel test series (A and B) using surface-mounted elements were conducted; then, V_s measurements using the conventional “tip-to-tip” bender elements were performed to obtain the “accurate” reference value. For both “tip-to-tip” and “side-to-side” measurements, different measure distances in a sequence of 40, 30, 20, and 10 cm were arranged. The penetrating length of bender element was 1 cm into the soil. For a given measuring distance, a single sine wave input was used with a frequency changing stepwise in series of 0.5, 1, 2, 4, 8 and 16 kHz to seek the optimal responses, and the received signal was stacked for about 100 times.

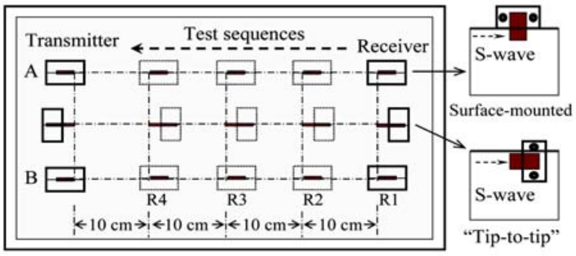


Fig.3 Arrangement of V_s measurement in model ground

TEST RESULTS AND ANALYSES

In this section, test results in both conventional and surface-mounted arrangements are similarly treated and compared, to identify the differences between these two types of measurements and clarify the testing techniques for surface-mounted bender elements.

Measurements of conventional “tip-to-tip” type

Fig.4a shows the typical signals of the conventional type at tip-to-tip distance L_{tt}=212 mm with different input frequencies, where no obvious dispersion is observed at the near surface part of sand model. Fig.4b shows the signals at different travel distances. Since the polarizations of the transmitter and receiver are known and kept constant during test, the travel time can be readily determined by the “time domain first arrival method” with consideration of near field effect (Kawaguchi *et al*., 2001), which treats the zero-crossing point after the first bump as the arrival of shear wave. The V_s values at different distances keep constant as shown in Fig.5.

Since all the receiving signals in Fig.4b have almost the same shape and frequency responses, the travel time between neighboring receivers was also evaluated from cross-correlation technique by using the following Eq.(2) (Viggiani and Atkinson, 1995; Bartake and Singh, 2007) to check the reliability of the handpicking first arrival method:

$$CC_{xy}(\tau)=\lim_{T\to\infty}\frac{1}{T}\int_0^T X(t)\cdot Y(t+\tau)\mathrm{d}t, \tag{2}$$

where $CC_{xy}(\tau)$ is cross-correlation function, T is recording period, $X(t)$ is time history of input wave, $Y(t)$ is time history of received wave, and τ is delay.

Fig.6 shows a typical calculation, where the peak nearest to the value of unity in the time history of cross-correlation was taken as the required arrival time. Fig.7 shows a comparison between the velocities determined by the cross-correlation and the first arrival methods. As shown in Fig.7, the shear wave velocities determined by both methods are almost the same when the triggering frequencies are higher than 2 kHz. Therefore the results of conventional “tip-to-tip” type are taken as the correct measurements, namely, V_s=112.7 m/s for this model surface.

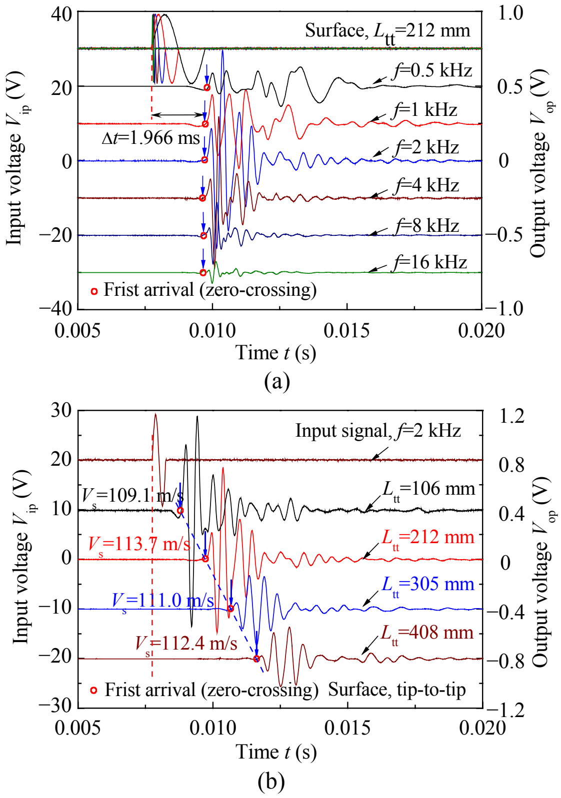


Fig.4 Conventional “tip-to-tip” measurement at different frequencies (a) and different travel distances (b)

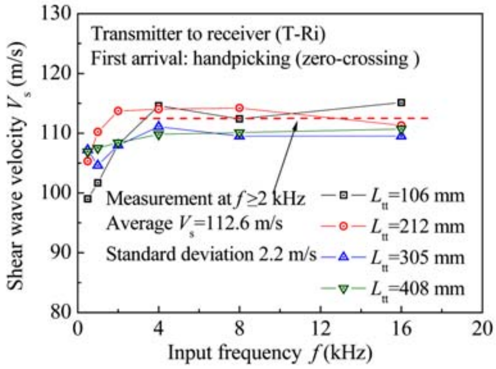


Fig.5 V_s determined by the first arrival method

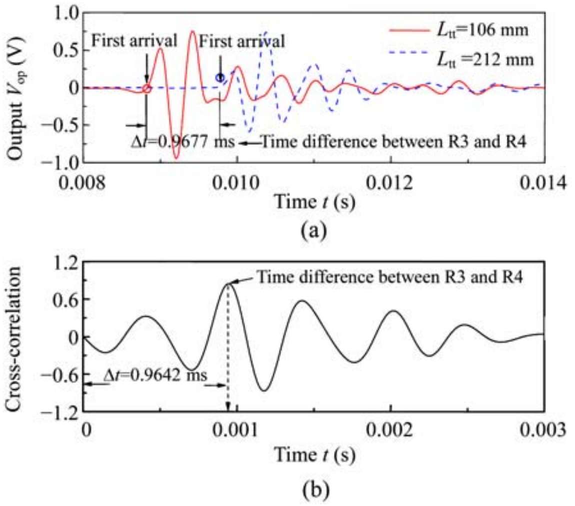


Fig.6 Time delay between two arrivals. (a) Handpick method; (b) Cross-correlation method

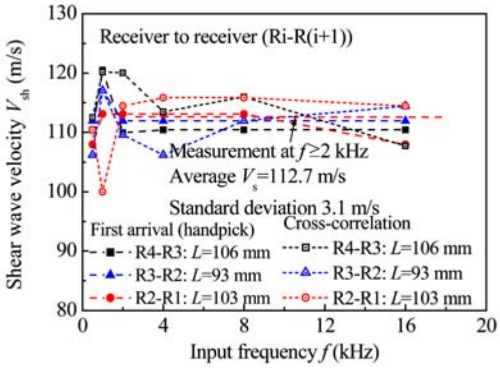


Fig.7 Comparison of V_s determined from the handpick and cross-correlation methods

Measurements of surface-mounted “side-to-side” type

Fig.8 shows the testing signals of Series A at “edge-to-edge” distance L_{ee}=96 mm. The frequency responses are similar to those of conventional “tip-to-tip” type, and the signals are clear enough to identify the first arrival. Meanwhile, it is shown in Fig.8 (or Fig.4a) that, even at frequencies from 1 to 8 kHz where the intrinsic dispersion effects would not be expected, the input frequency should routinely be varied during testing in order to obtain the high quality receiving signal, so that the first arrival of shear waves could be readily determined.

Fig.9a illustrates the receiving signals at different distances of testing Series A with frequency 2 kHz. The first arrival of the received signals at different travel distances falls on one inclined line (dashed), which implies that the shear wave velocities at different distances are almost the same. By plotting the travel distance against the travel time determined by first arrival method as shown in Fig.10a, one may find that the fitted line from “edge-to-edge” distance will trace back to the coordinate origin, while that from “center-to-center” distance will intercept the vertical coordinate at 12.9 mm, which value is almost the same as the width of bender elements. Moreover, the V_s values calculated based on L_{ee} are very close to the reference value mentioned above, while those obtained from L_{cc} are slightly higher and the error increases as the distance decreases, reflecting the influence of bender element size. Similar results obtained in testing Series B are shown in Figs.9b and 10b. These findings imply that the correct travel distance in testing of the surface-mounted bender elements should be determined from “edge-to-edge” rather than from “center-to-center”.

On the other hand, by comparing the received signals in Fig.9a or Fig.9b with those in Fig.4b, one may find that the responses at receiving element are weaker in surface-mounted test than that in conventional test, which agrees with those found by Lee and Santamarina (2005). Such results suggest the importance of selecting appropriate travel distance for high quality signals. Nevertheless, the attenuation feature in surface-mounted measurements offers the possible opportunity to study the damping characteristics of soils (Wang *et al*., 2006).

To check the reliability of the “time domain first arrival” method in travel time determination, the V_s values obtained from the first arrival and cross-correlation methods are plotted in Figs.11a and 11b, respectively, where the reference value (i.e., V_s=112.7 m/s) determined from the conventional “tip-to-tip” type test is also indicated. It is clearly shown that, at the range of frequency ≥2 kHz, the velocities determined by both methods are the same and very close to the reference value (error<3%). Therefore the “time domain first arrival” method is recommended for the

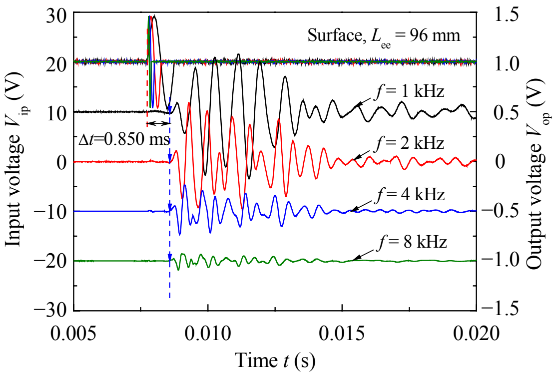
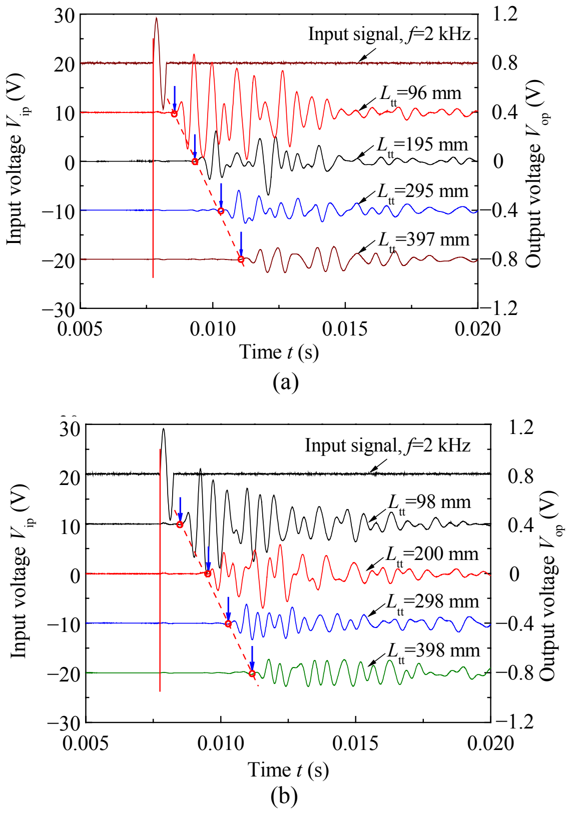


Fig.8 “Side-to-side” measurement at different frequencies



(a)

(b)

Fig.9 “Side-to-side” measurements at different distances. (a) Series A; (b) Series B

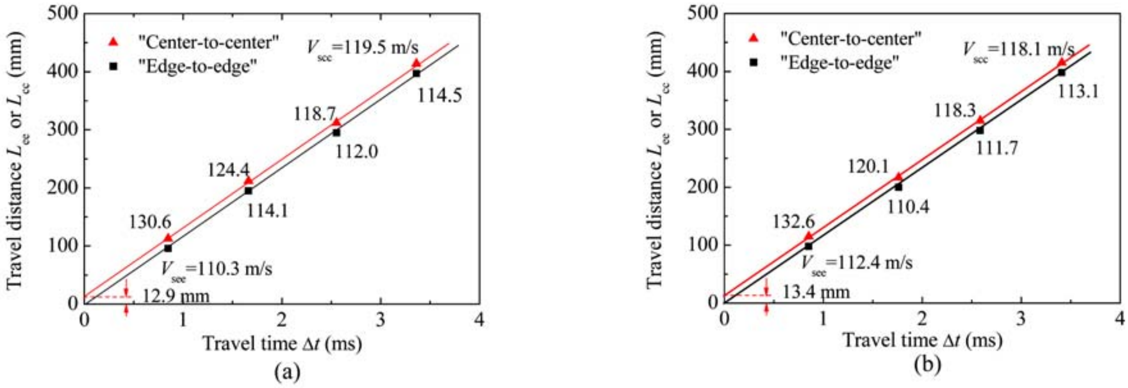


Fig.10 V_s at different travel distances. (a) Series A; (b) Series B

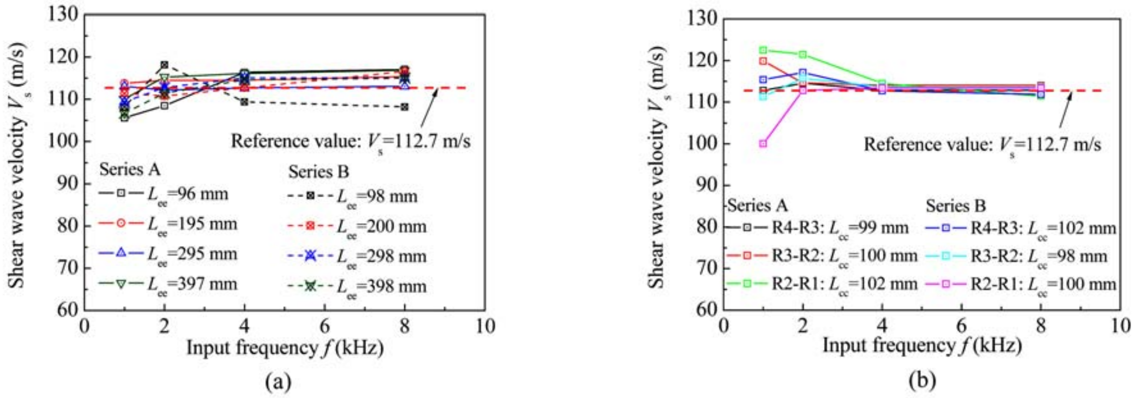


Fig.11 V_s determined by (a) the first arrival method and (b) the cross-correlation method

travel time determination in the tests using surface-mounted bender elements. The cross-correlation method is also recommended as an alternative to check travel time determination since the present system benefits from the multiple receiver arrangement.

CONCLUSION

The present study proposed a surface-mounted bender element system for measuring horizontal shear wave velocity in the surface of soil, where the "side-to-side" arrangement is adopted for the transmitter and receiver elements. Comparison tests between two different alignments were performed on model ground of silica sand No. 8 to check the feasibility and reliability of this system.

Test results showed that, as long as taking the inside "edge-to-edge" distance as the travel distance and determining the travel time by the "time domain first arrival method", the surface-mounted "side-to-side" bender elements will perform as accurately as that of the conventional "tip-to-tip" type, giving repeatable and relatively precise (error<3%) measurements of horizontal shear-wave velocity over the frequency range 2~10 kHz.

The present surface-mounted bender elements feature its ability to adjust the measuring distance, the penetrating length of piezoelectric patch, and the types of "source to receiver" arrangement, which allows flexible measurements for soils with different geometries and stiffness both in laboratory and in the fields. For instance, multiple-receiver arrays allow comparison of the same wave passing two similar receivers, and facilitate the use of cross-correlation to give objective numerical determinations of travel time. Therefore the present system offers a promising nondestructive tool for characterizing geomaterials such as soil disturbance assessment and quality check of soil improvement.

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