IN-SITU STIFFNESS EVALUATION OF SOFT GROUND USING BENDER ELEMENTS

J.W. Jung[1], H.S. Kim[1], B.C. Kim[2], I.B. Park[1] and Y.J. Mok[3]

[1]Research Assistant, Dept. of Civil Eng., Kyunghee University, Korea.
[2]Assistant manager, LOTTE Eng. & Construction, Yongsan-gu, Seoul, Korea.
[3]Professor, Dept. of Civil Eng., Kyunghee University, Yongin-si, Korea(corresponding author)
Email: yjmok@khu.ac.kr

ABSTRACT :

A new seismic probe, by utilizing favorable features of bender elements, crosshole and seismic cone techniques, has been developed in order to enhance data quality and easiness of testing. The basic structure of the probe, called "MudFork", is a fork composed of two blades, on each of which source and receiver bender elements were mounted respectively. Much effort was exerted to reduce noise transmitted through the frame from the source to the receiver bender, cross-talk caused by high voltage driving the source bender and coating of the elements against salty water. The prototype probe has been developed through extensive in-house program to optimize in terms of data quality and installation convenience. The first prototype probe was penetrated in coastal mud using SPT(standard penetration test)rods pushed with a routine boring machine and shear waves signals were measured. The shear wave signals were so excellent that the first arrival time can be easily identified. The shear wave velocity profile was validated with the laboratory measurements of shear wave velocities of specimens sampled.

KEYWORDS : Mudfork, Shear wave velocity, Undrained shear strength, Bender elements

1. INTRODUCTION

Ground stiffness (shear wave velocity) is one of the key parameters in earthquake geotechnical engineering. Various in-situ and laboratory testing techniques have been developed and used to measure the parameter properly. Among the techniques, borehole seismic methods including cross-hole, down-hole and in-hole tests are wildly used, but their complexities involving testing equipment and installation of boreholes hinders their usage (Mok et al. 2005). In an effort to eliminate boreholes, a hybrid technique (called seismic cone) was developed by mixing favorable features of cone penetration and down-hole tests (Campanella et al. 1986). Another hybrid technique was just born by developing a penetration-type seismic probe and adopting cross-hole testing scheme. The key features of the technique are the probe consisting of a pair of tiny source and receiver, and convenience in data acquisition in soft soils.

2. BASIC CONCEPTS FOR PROBE DESIGN

2.1. Adopting Bender Elements

A bender element consists of two piezoceramic sheets sandwiching a central metal shim as it is shown in Figure 1. Bender elements can be made into various shape, size, and arrangement of piezoceramic sheets and metal shims. The bender element can bend as piezoceramic sheet on one side expands while the other side contracts with an applied voltage. Expanding and contracting of the sheets are reversed as the direction of the voltage is changed. Thus, application of an AC voltage enables the element vibrate and be used as an actuator (seismic source). On the other hand, if the element is deformed by outside force, it generates voltage and can be used as a receiver. The three layers of inner, silver and skin coatings, are for electric isolation, shield and water-tight, respectively. The element, used herein as a source and receiver, has favorable features such as simple principle of energy conversion, excellent control capability and tiny physical size (7x12mm), compared to the intricate mechanical sources and electro-magnetic receivers (geophones) used in routine cross-hole tests. The drawback of the element is that the energy for ground perturbation is small and the maximum measurement distance is within the order of half meters. The source and receiver elements, thus, are to mount on a frame in the sense of miniature cross-hole fashion.

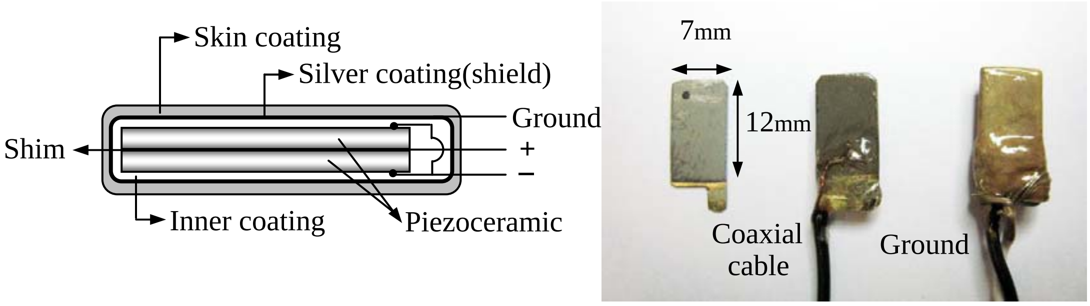


Figure 1 Structure of a bender element

2.2. Basic Configuration of the Probe

A pair of source and receiver elements was mounted on a frame. A crucial side effect of the mounting scheme is that the vibration propagating through the frame from the source to receiver (hereafter called noise) interfere the "signature wavelet" of shear wave energy through soil. In the early stage of the research, a damping device intercepting the noise was in vain attempted. A decisive and fortunate founding was concluded, through extensive laboratory work, that the plate-shape frame could radiate the noise through, if intimately contacted, the surrounding soil and save the formidable effort to invent a damping devise. In other words, the contact area with ambient soil is, thus, the key parameter for the reduction of the noise. The contact area of 100 ㎠ was found to be enough to dissipate most noise and record quality signals (Mok et al. 2007; Jung et al. 2008). After several different shapes tried, the fork-type frame with two blades was finalized and called "MudFork" as shown in Figure 2.

3. MUDFORK

MudFork consists of two blades bolted down at the stem and a adapter to SPT(standard penetration test) rods as shown Figure 2 and 3. The distance between two blades is in the order of 70mm and therefore the net distance between source and receiver elements is 55-60mm in order to fit in 76mm-diameter casing installed just in case near surface. A triangular fin was welded at the end of each blade to incise the ground prior to the bender element to reduce the abrasion of the element during penetration. To reduce the disturbance of the raypath crossing zone between two bender elements, the edge of the thin blade was sharpened outside only to divert the upcoming soil outward.

The detailed dimensions of the probe are shown in Figure 3. The blade was 3cm wide, 16cm long and 4mm thick and the contact area hence was about 60 ㎠. The total contact area of two blades was 120 ㎠ more than enough to dissipate the noise through ambient soil. The source and receiver elements were mounted on each blade facing each other using threaded nylon bolts in an attempt to isolate the noise further. The two blades were assembled by bolting at the stem with a sandwiched piece of nylon as another scheme of noise reduction.
The probe was penetrated in field using SPT rods by pushing with a routine boring machine. The probe was penetrated quite well in soft layers. However, the blade of the fork was bent at the joint of blade and stem in

sand or silt seam as shown in Figure 4. The blade was reinforced by welding a stiffener on the outside to increase the moment of inertia as shown in Figure 5.

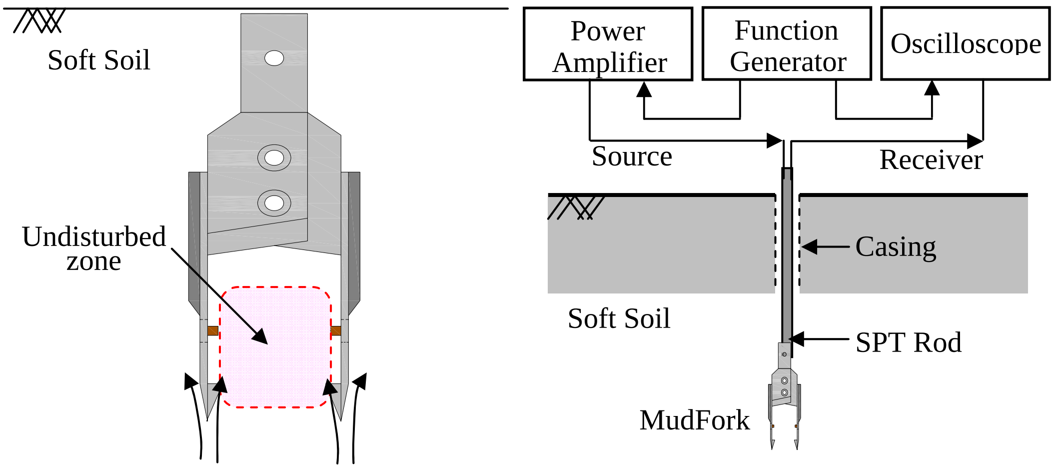


Figure 2 MudFork and testing configuration

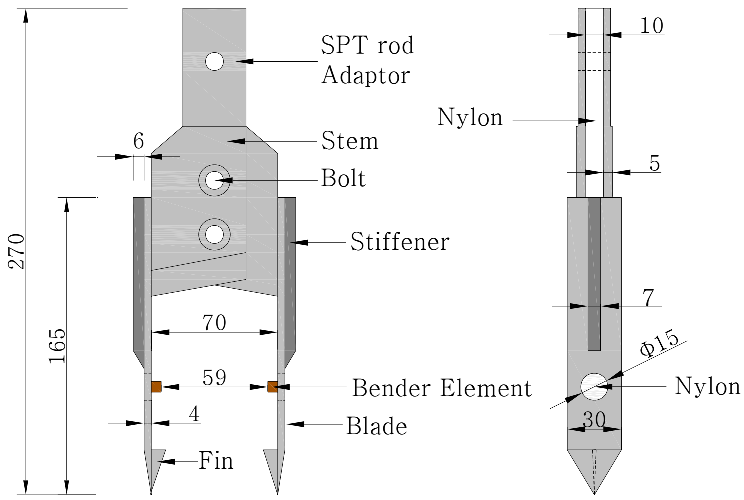


Figure 3 Detailed dimension of MudFork

The driving voltage of the source is as high as 20-30 volts and may cross over to receiver cable. To reduce the cross-talk and electrical noise, positive and negative electrodes were shielded with silver coating, which was in turn connected to ground line (see Figure 1). A shielded coaxial cable, with a ground line and outer woven shield under jacket, was used. Also two separate cables were connected to source and receiver bender elements, respectively, for further mitigation of cross-talk.

4. LABORATORY EVALUATION

To evaluate the disturbance effect during probe penetration, shear wave measurements were performed in a kaolinite slurry chamber, whose diameter and height were 57cm and 80 cm, respectively as shown in Figure 6. A pair of rods was instrumented with 7 bender elements, one set for source and the other for receiver, with the even spacing of 10 cm. The instrumented rods were installed 20cm apart for miniature cross-hole testing. As the slurry being stabilized, shear wave velocities of the slurry were measured using cross-hole test with each pair of source and receiver elements at each depth. The shear wave signals, whose first arrival times indicated with arrows, were shown in Figure 7. Then the shear wave velocities were measured at every depth of 5cm by penetrating the MudFork. The signals exhibits "signature wavelet" and the first arrival times were notated with the arrows as shown in Figure 8. The comparison of the shear wave profiles from cross-hole and MudFork demonstrates the minimal disturbance effect due to the penetration action as shown in Figure 9.

Figure 4 Deformed MudFork during penetration

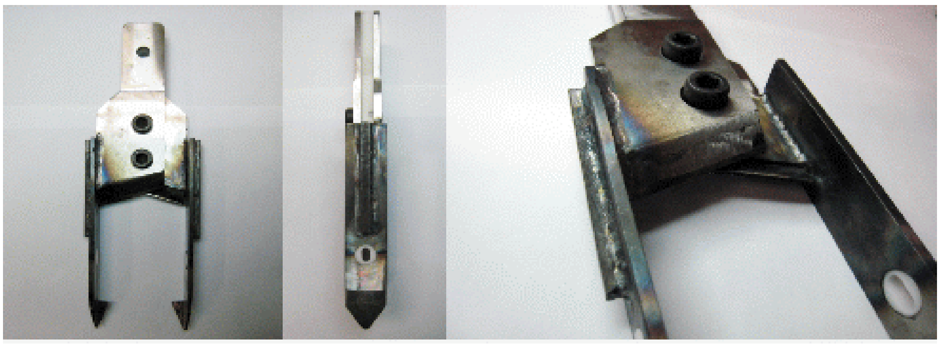


Figure 5 MudFork reinforced with stiffeners

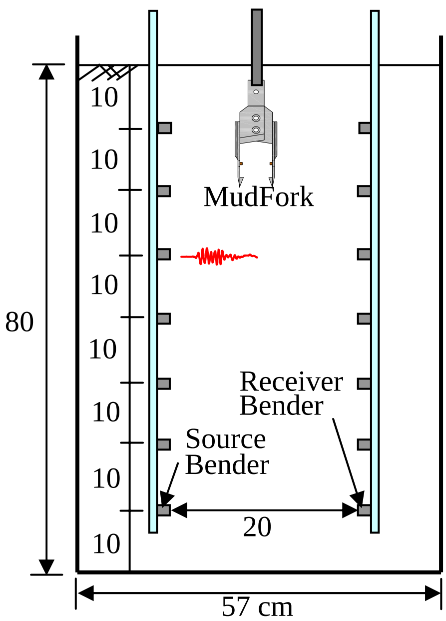


Figure 6 Slurry chamber with instrumented rods

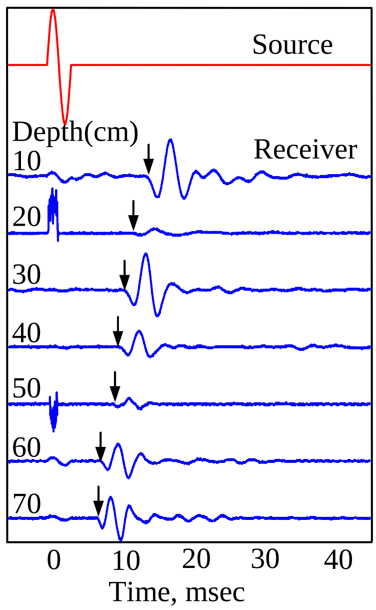
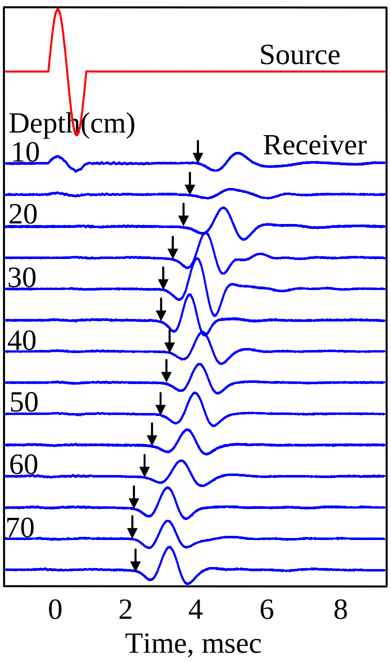


Figure 7 S-wave signals from cross-hole



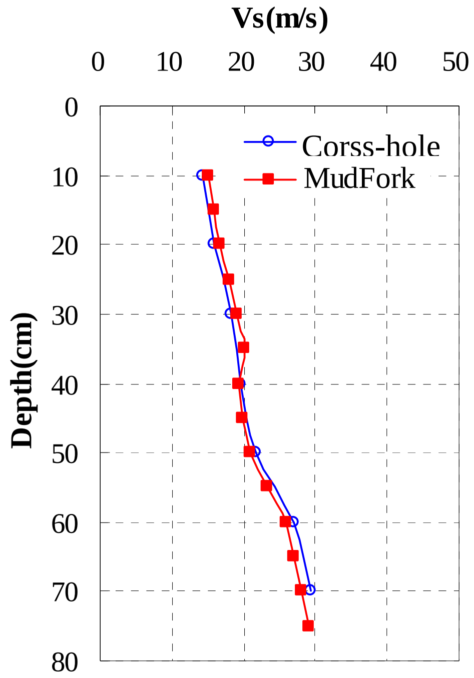


Figure 8 S-wave signals from MudFork

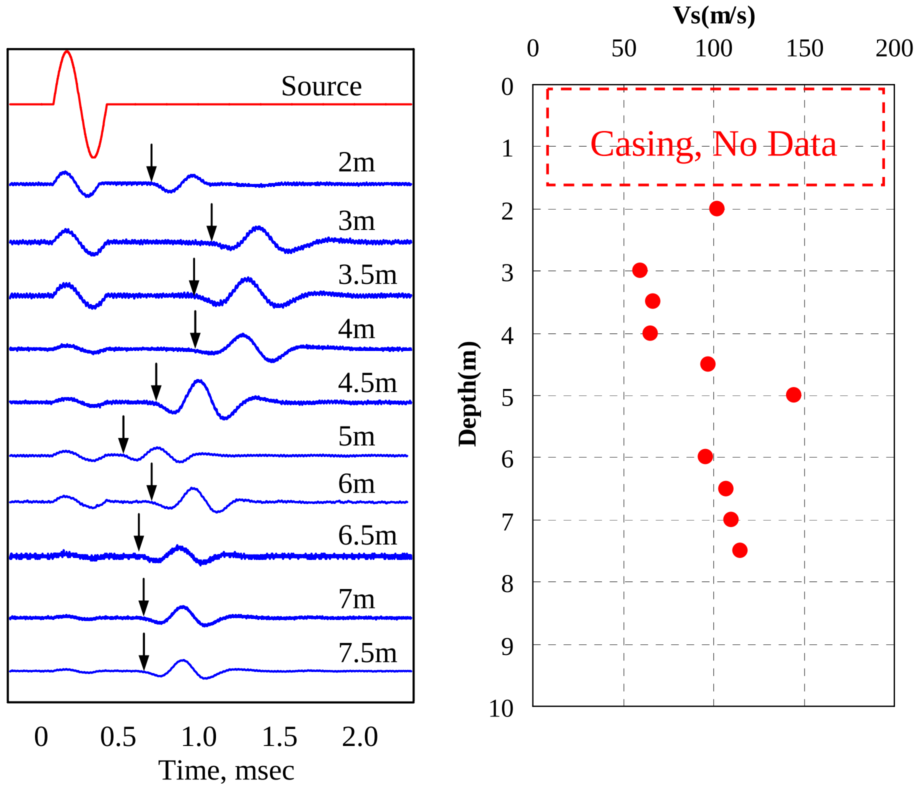
Figure 9 Comparison of S-wave velocity profiles

5. FIELD APPLICATION

The probe was penetrated at a PBD(plastic board drain) site near Incheon, Korea, to measure shear wave velocity. The site consists of silty soil as deep as 10meters and includes thin fine sand seams. The top layer of gravelly fill was removed by shoveling and upper desiccated hard layer (about 1 meter deep) was drilled and cased. Shear wave measurement was carried out at every half meters up to 7.5 meters by penetrating the probe using a boring machine. The MudFork connected to SPT rods prior to pushing is shown in Figure 10. The shear wave signals measured at each measurement depth are shown in Figure 11a. The mechanical noise prior to “signature wavelet” of shear wave is completely eliminated, except for low level cross-talk of the same cycle of sine wave as source signal. The signals are decent enough to identify first arrival times of shear wave. The first arrival times of shear wave are in the range of 0.5-1.0msec. Net travel distance between the source and receiver is 59mm. The shear wave velocities in the range of 60-150m/sec. were obtained by dividing the travel path with the first shear wave arrival times as shown in Figure 11b. The driving voltage and frequency of the source was 30 volts and in the range of 2.4-4.5 kHz, respectively. The driving frequency is high enough to maintain more than two wave lengths of the shear wave within the ray path (59mm), which is to eliminate the near field effect on the first arrival of shear wave. The shear wave velocities are linearly increased with depths, as represented by a straight line shown in Figure 12b, except abrupt change at the sand seam near the depth of 5 meters.

To verify the results and evaluate the performance of the probe, a cone penetration test (CPT) was performed. Also a boring was drilled and undisturbed samples were taken at the depth of 3, 5, and 8 meters to measure undrained shear strength and shear wave velocity as well in the laboratory. The upper portion of the samples seemed to be somewhat experienced disturbance and as many specimens as possible were prepared with the middle and lower portions of the samples. The sample taken at the 5 meters contained more sand than silt. The portion abundant with sand was discarded and the specimens were trimmed from the portion containing much silt. Before shearing the specimens in the triaxial cell, shear wave velocities were measured using bender elements installed at the top cap and base pedestal of the cell (Oh et al. 2008). To mitigate disturbance effects, the specimens were recompressed with the isotropic confining pressure equivalent to in-situ effective stress.

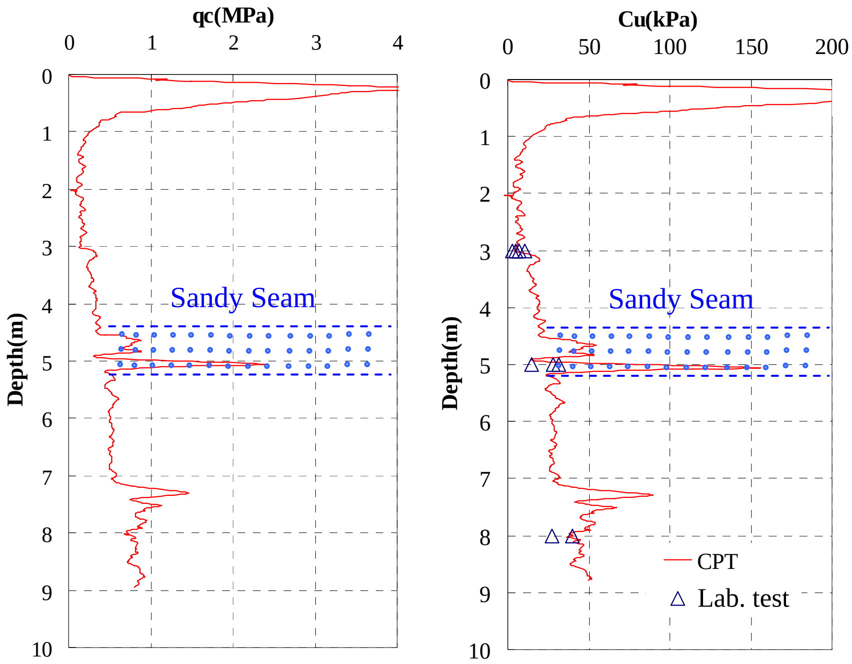
Figure 10 MudFork set up in field



a) S-wave signals b) S-wave velocity profile

Figure 11 S-wave signals and s-wave velocity profile

The laboratory values, both measured before and after recompression, are shown along with field values in FIG. 8-b. The recompression seemed to mitigate the disturbance effect on the stiffness. The increase might partly be caused by the density changes as Jamiolkowski et al.(1985) indicated the limitation of the technique. The values at 5 meters somewhat are off the linear increment with depth in higher side due to gradation difference by sampling at the sand seam. The disturbance effect was also evaluated in terms of shear strength. The CPT tip resistance also increases linearly with depth, except for the values of the sand seam near the depth of 5 meters as shown in FIG. 12-a. The undrained strength was calculated from the tip resistance q_u with the value of cone factor, N_k =15, as suggested by Robertson and Campanella(1998), and plotted with the values measured from triaxial tests as shown in FIG. 12-b. The values of undrained strength, C_u from recompressed specimens are very close or little off to field values in lower side. The recompression thus seemed to work positively in mitigation of the disturbance effect. The shear wave velocities measured with MudFork are little higher than the laboratory values, and the degree of disturbance caused by the penetration of blades, can be concluded to be minimal.



a) Cone tip resistance   b) Undrained strength

Figure 12 Cone tip resistance and undrained strength profiles

6. CONCLUSIONS

A probe "MudFork" was developed, by utilizing favorable features of conventional testing techniques and bender elements, to measure the stiffness of soft soils accurately and easily. The performance of the probe was evaluated by comparing the field and laboratory values of the stiffness. The findings are as below.

1. The probe works well in terms of data quality and testing convenience.
2. The structure of the probe, consisting of two blades, is very effective in dissipation of mechanical noise and reduction of ground disturbance during penetration.
3. A collective evaluation of the disturbance effect during penetration is needed.
4. The probe can be a practical tool for stiffness evaluation of soft soils by further refinement.

ACKNOWLEDGEMENTS

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