IJR International Journal of Railway
Vol. 1, No. 2 / June 2008, pp. 64-71

The Korean Society for Railway

A Tentative Methodology for Quality Control of Trackbed Fills Using Field and Laboratory P-Wave Measurements

Chul-Soo Park*, In-Beom Park*, Eun-Jung Kim*, and Young-Jin Mok†

Abstract

The quality of track-bed fills of railways has been controlled by field measurements of density (γ_d) and the results of plate-load tests. The control measures are compatible with the design procedures whose design parameter is k_{30} for both ordinary-speed railways and high-speed railways. However, one of fatal flaws of the design procedures is that there are no simple laboratory measurement procedures for the design parameters (k_{30} or, E_{v2} and E_{v2}/E_{v1}) in design stage. A new quality control procedure, in parallel with the advent of the new design procedure, is being proposed. This procedure is based upon P-wave velocity involving consistently the evaluation of design parameters in design stage and the field measurements during construction. The key concept of the procedure is that the target value for field compaction control is the P-wave velocity determined at OMC using modified compaction test, and direct-arrival method is used for the field measurements during construction. The procedure was verified at a test site and the p-wave velocity turned out to be an excellent control measure. The specifications for the control also include field compaction water content of OMC ±2% as well as the p-wave velocity.

Keywords : *Railway track-bed, Quality control, P-wave velocity, Compaction test, Direct-arrival method*

1. Introduction

The quality of compaction fills for railroad track-beds has been controlled by field measurements of density (γ_d) and the results of plate-load tests. For ordinary-speed railways, the coefficient of soil reaction (k_{30}) (KS F 2310) is the control measure, parallel with 90 - 100% relative density [1]. In the other hand, the deformation modulus and modulus ratio (E_{v2} and E_{v2}/E_{v1}), based upon repeated plate-load tests (DIN 18 134), are used for quality control with supplement of the relative density requirement for high-speed railways [2]. Each control measure is compatible with the design procedures whose design parameter is k_{30} for both ordinary-speed railways and high-speed railways.

However, one of fatal flaws of the design procedures is that there are no simple laboratory measurement procedures for the design parameters (k_{30} or, E_{v2} and E_{v2}/E_{v1}) in design stage. The values of the design parameters are either evaluated or, assumed and confirmed later on, using field plate-load testing prior to the productive stage of construction. This defect is compensated with laboratory compaction tests (density-water content relationship) and field density measurements. Thus, a specific relationship is required to span the density and each of the design parameters, whose value should be met in quality control. The plate-load test often uses 30 cm in diameter plate to evaluate k_{30} and, E_{v2} and E_{v2}/E_{v1}. The plate is too small to use in track-bed fills containing as large a boulder size as 30 cm in diameter such as crushed rock-soil subgrade, which often encounters in construction sites for the new high-speed railway.

Recently, a new design procedure has been developed using an elastic multi-layer model under the premise of a simple and reliable method of determining resilient modulus [3]. An alternative method of determining the resilient modulus, which is easy enough for the practice engineers to carry out, was also proposed using dynamic properties. The elastic wave velocities are the initial part of the modulus reduction curve at small strain and are in turn consistently related with the resilient modulus [4]. Thus, it is rational to use the elastic wave velocities as the quality

†Correspond author : Professor, Dept. of Civil Engrg., Kyunghee Univ.
E-mail : yjmok@khu.ac.kr; TEL : (031)201-2927; FAX : (031)202-8854
*Research Assistant, Dept. of Civil Engrg., Kyunghee Univ.

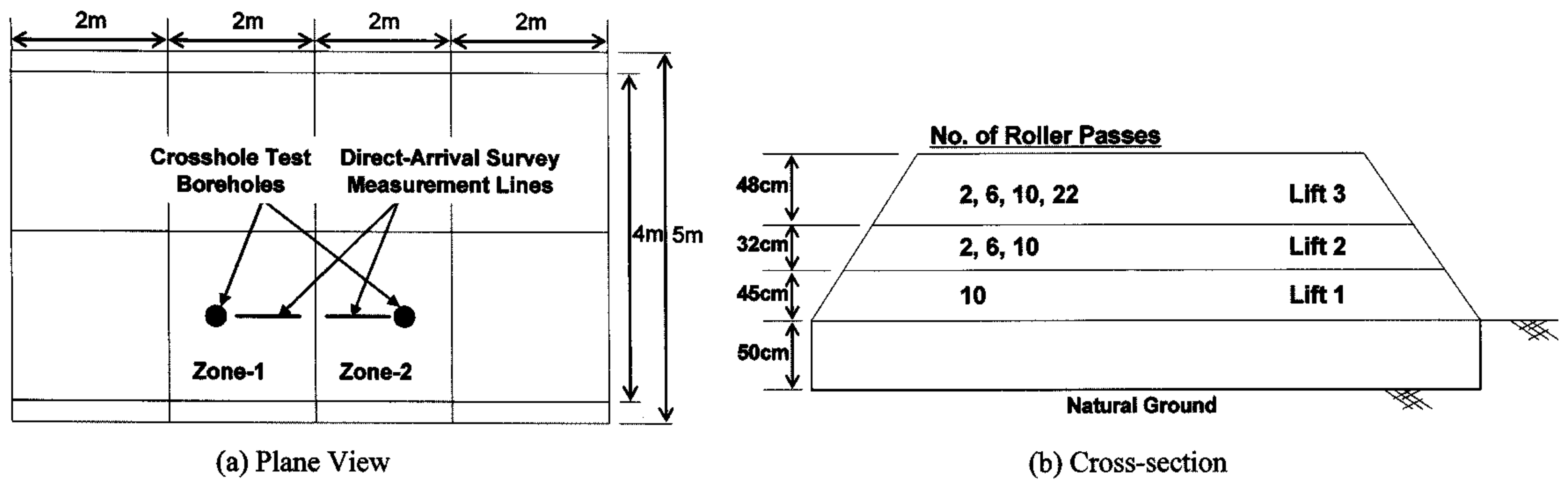


Fig. 1 Schematic Diagram of the Test Fill

control measures. The P-wave velocity was adopted to develop a new quality control procedure [5]. The key concept of the method is that the P-wave velocity at OMC (optimal moisture content) is the target value for field compaction control and field values measured during construction is required to meet the target value. That is, the methodology follows exactly the same procedure as the density control, except the density being replaced by the P-wave velocity. One of the key features of the method is that the P-wave velocity measurements can be carried out with minor modification of the laboratory compaction test and the results can be used for both the determination of the resilient modulus in design stage and quality control guidelines in construction stage. In the study, the proposed procedure was verified at a test fill in the compound of KRRI (Korea Railroad Research Institute).

2. Testing Program

2.1 Test Fill

In the compound of KRRI, the test fill (8 m long, 5 m wide and 1.25 m high) was constructed with 3 lifts as shown in Fig. 1. The original ground was excavated as deep as 0.5 m and compacted again for intimate contact and the reduction of impedance contrast between original ground and the first lift. Each lift was compacted by a 12.5 ton vibratory roller with the target thickness of 0.3 m. The final thickness of each lift was determined by level surveying as 0.45 m, 0.32 m and 0.48 m from the first lift to the top lift. The test fill was subdivided into 8 zones. Our testing was allotted to zone 1 and 2 along with other research teams.

2.2 Testing Program

The testing program consists of laboratory and field measurements as shown in Table 1 In laboratory, P-wave velocities were measured during associated compaction tests and also resonant column tests were carried out to evaluate the nonlinear shear modulus and the stress effect on P-wave velocity using the specimens remolded at OMC. In the field, Direct-arrival method was adopted to measure the increment of P-wave and S-wave velocities as the roller passed on each lift. Also, field density was measured using sand cone method. The final thickness of each lift was surveyed with leveling. The final P-wave and S-wave velocity profiles were determined by cross-hole measurements.

3. Laboratoty Measurements

3.1 Modified Compaction Test

Disturbed samples were collected from the test fill and the modified compaction test (D type, KS F 2310) was adopted to evaluate the P-wave velocity vs. water content

Table 1. Testing Program

	Testing Method	Measurement
Laboratory	Modified Compaction Test	V_P & γ_d - w Relationship, V_P at OMC
	Resonant Column Test	E - ε Relationship, Effect of σ'_m on V_p
Field	Direct-Arrival Method	V_P and V_S vs. No. of Roller Passes
	Cross-Hole Test	V_P, V_S, and ν Profiles
	Field Density	In-Situ γ_d and w
	Level Surveying	Thicknesses of Each Lift

relationship as well as the relationship between dry unit weight and water content. P-wave velocities were measured by attaching a PCB accelerometer (voltage type, PCB 353B11) at one end of the mold and impacting the other side with an instrumented hammer (PCB 086C80). The procedure was described in detail by Park et al. (2008b). The measurements was carried out in the air without applying further confining pressure because the confinement in the mold is roughly equal to the near surface confinement of each lift during field compaction [6]. P-wave signals measured from each compaction mold with varying water content are shown in Fig. 2. The variation of P-wave velocity and dry unit weight with water content was plotted in the same figure, whose left and right vertical coordinates are dry unit weight and P-wave velocity, respectively. The P-wave velocity curve follows the same trend of the dry unit weight variation except its shifting left and being rather asymmetric about OMC, whereas the dry unit weight curve is more or less symmetric. The P-wave velocity of the dry side of OMC is higher than the corresponding P-wave velocity of the wet side because the dry side is getting brittle whereas the wet side becomes ductile. The P-wave velocity at OMC (297 m/sec and 10.4%) was adopted as the target value for field quality control rather than the maximum value, by taking into account of the brittle nature and matric suction of the dry side of the optimum. In the specification, field compaction water content of OMC±2% should be supplemented to prohibit contractors from taking advantage of higher modulus at the dry side of the optimum.

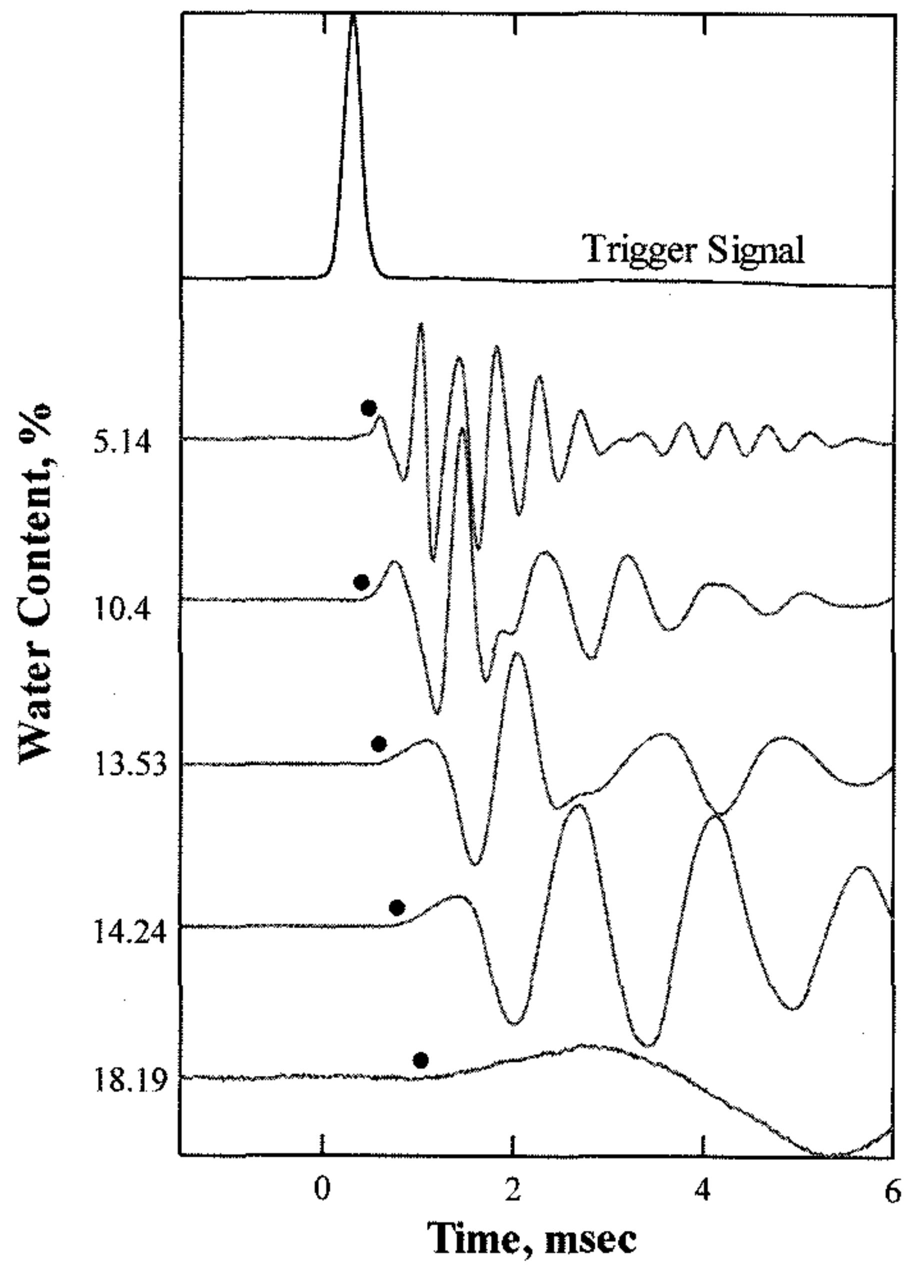


Fig. 2 P-wave Signals

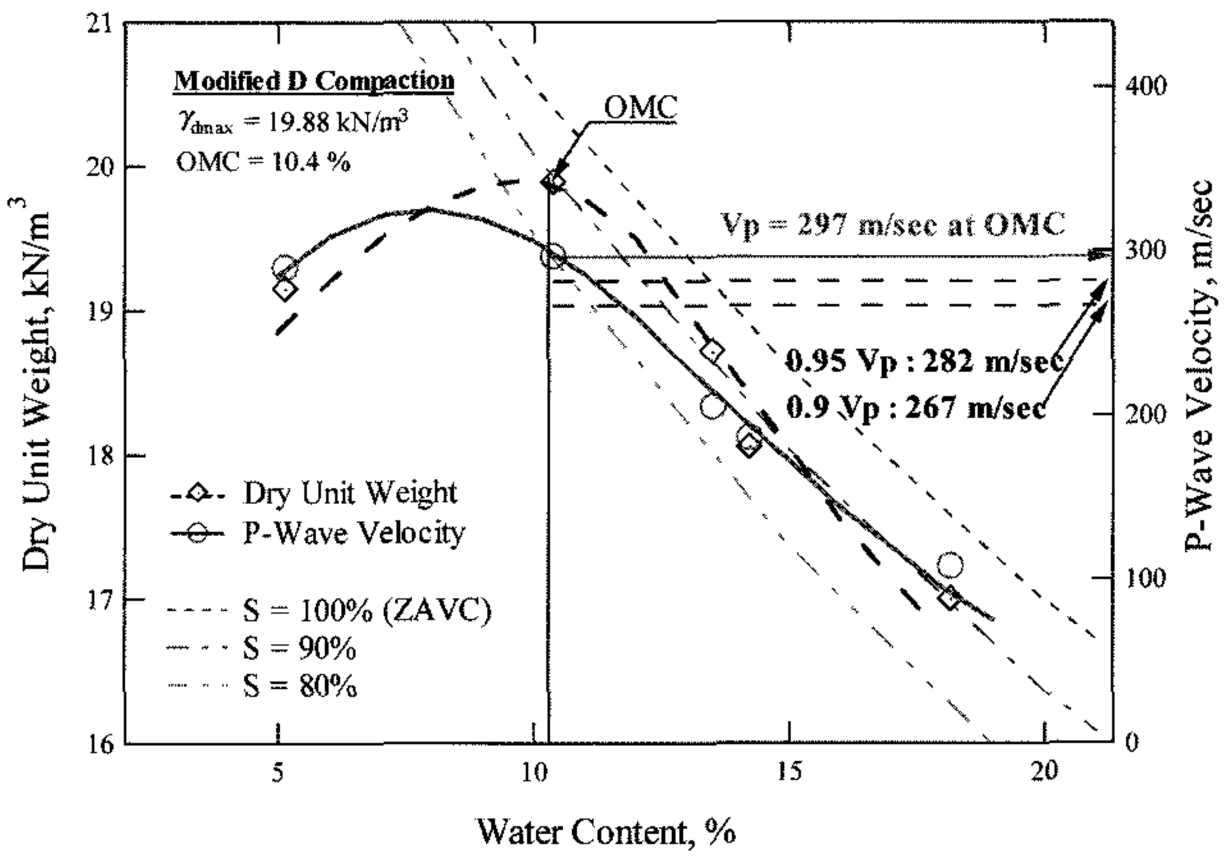


Fig. 3 Variation of Dry Unit Weight and P-wave Velocity

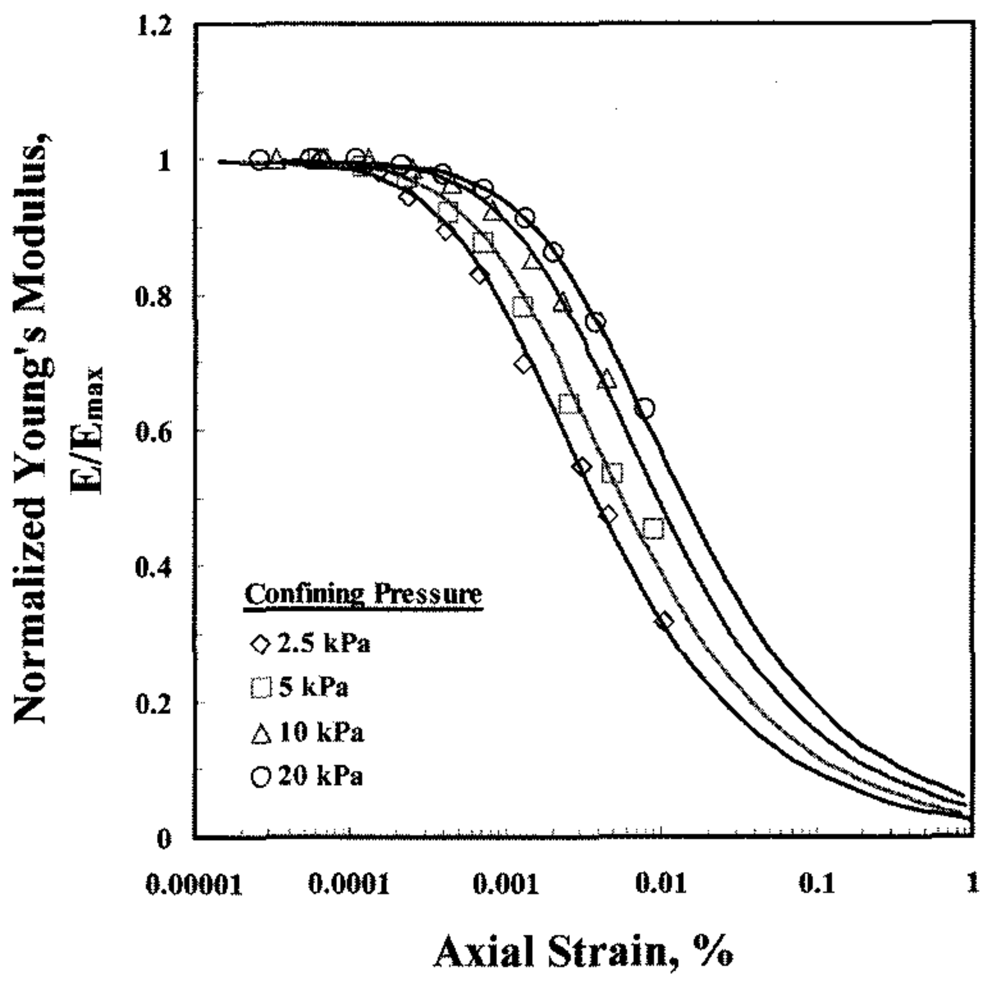


Fig. 4 Normalized Young's Modulus Curves

3.2 Resonant Column Test

Resonant column tests were carried out with the specimen compacted at OMC to use the results in the determination of the resilient modulus and to evaluate stress dependent shear modulus at small strain. The nonlinear shear modulus was measured to shearing strain of 0.01% with the confining pressures of 2.5, 5, 10 and 20 kPa, by taking into account of the overburden stress of the fill. The shear modulus (G) and shear strain (γ) were transformed into Young's modulus (E) and axial strain (ε), respectively with the Poisson's ratio (ν) of 0.3, which was measured by cross-hole test. The normalized Young's modulus reduction curves are plotted in Fig. 4 and the nonlinear portion of the reduction curve is shifting with increasing confinement.

The shear modulus at small strain of the specimen increased with increasing confining pressure with the rate of 0.46 in logarithm scale, which is called as coefficient of

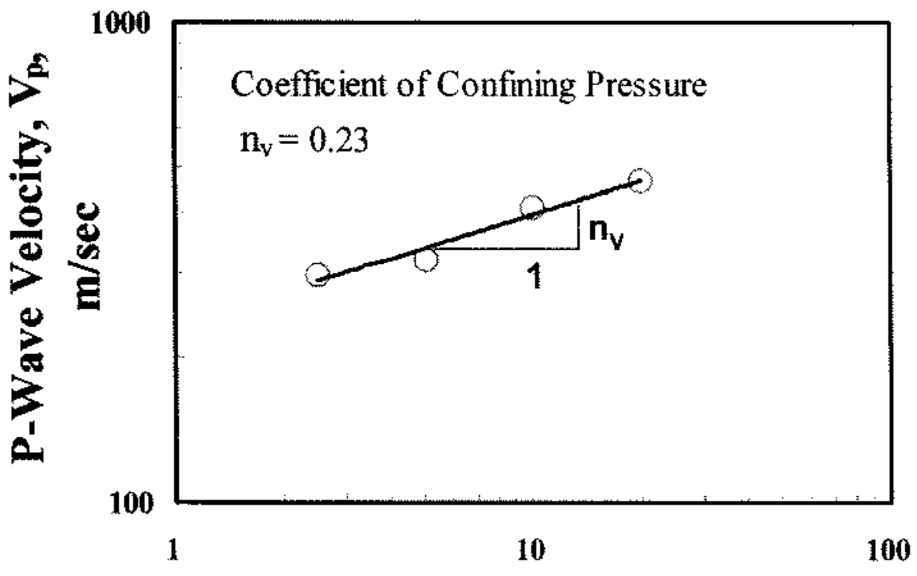


Fig. 5 Variation of V_P with Confining Pressure

confining pressure (n_v). The shear modulus was transformed into P-wave velocity with the Poisson's ratio (v) of 0.3 as shown in Fig. 5 and the n_v of the p-wave velocity is the half of that of modulus, that is 0.23, because elastic wave velocity is proportional to the square root of modulus.

4. Field Measurements

4.1 Direct-Arrival Method

Direct-arrival method is to measure near-surface elastic wave velocity with a source and an array of receivers laid on the ground surface as shown Fig. 6 [7]. This method is simple and reliable enough for practice engineers to be ready to access. This method is well suit for such a shallow and homogenous fill lift in terms of applicability and cost effectiveness. A sledge hammer head and a mid-size hammer were used to generate elastic waves as shown Fig. 7. Each receiver was planted with a spike for intimate contact with the ground. For P-wave measurements, horizontal impact was applied toward the receiver array and

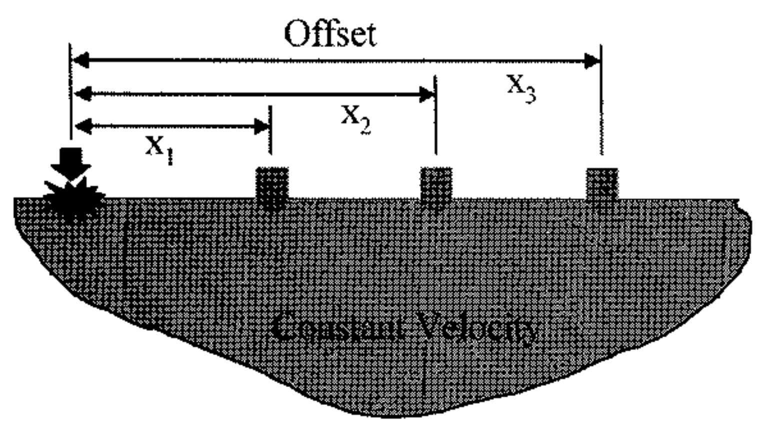


Fig. 6 Schematic Diagram of Direct-arrival Method

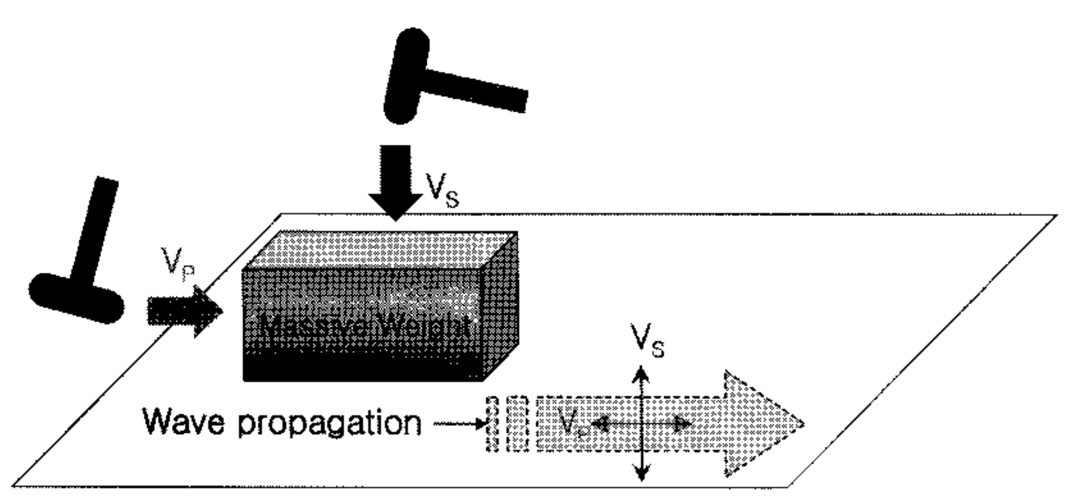


Fig. 7 Surface Source

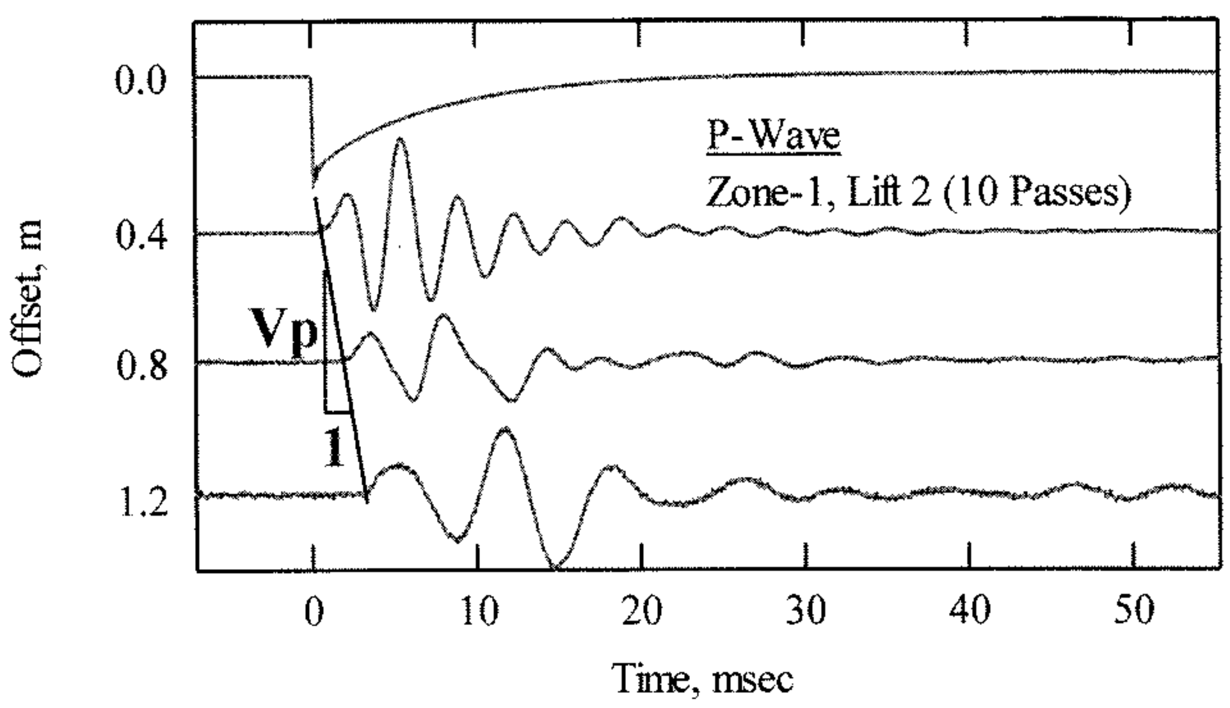


Fig. 8 Field P-wave Signals

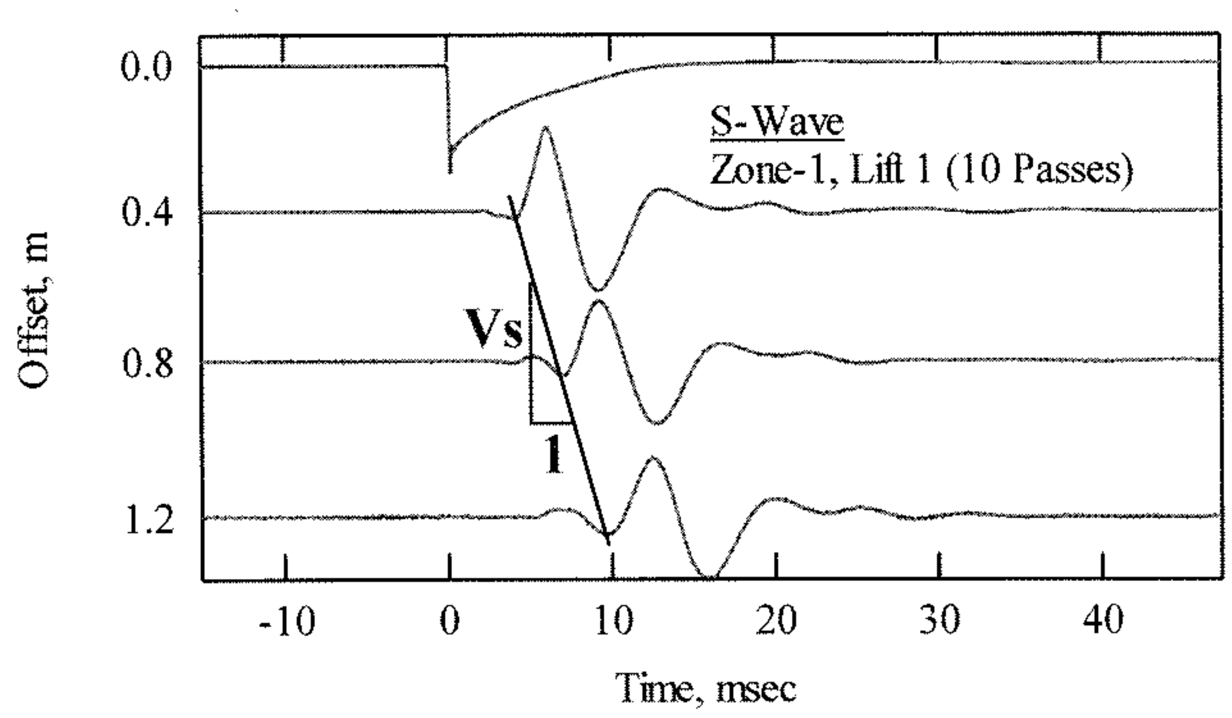


Fig. 9 Field S-wave Signals

horizontally-oriented receivers were used. For shear wave measurements, the combination of vertical impact and vertically-oriented receiver was used.

For each measurement, the P-wave or S-wave signals were stacked about offset as shown Fig. 8 and 9. The stacked signals give the distinct trace of the initial arrival times (denoted with the straight lines in the figures) and the inverse of the slope of each straight line is the P-wave or S-wave velocity. Excellent repeatability was shown through out the measurements.

Elastic wave velocities were measured after the rollers passed 2, 6, 10, 22 times on each lift of zone 1 and 2. This measurement scheme was partially fulfilled by field circumstances. The increasing trend of the elastic wave velocity with number of roller passing is shown along with the target values determined in laboratory (for instance, V_P at OMC) in Fig. 10 and 11. Both P-wave and S-wave velocities were very consistent in each lift and also resulted in Poisson's ratio of 0.32 consistently. The target value of S-wave was determined by P-wave velocity and Poisson's ratio of 0.32. The field values somewhat increased rapidly at lower number of pass, reached to the target value around 10 passes and were flattened later on. This performance manifests the P-wave velocity as an effective indicator for quality control.

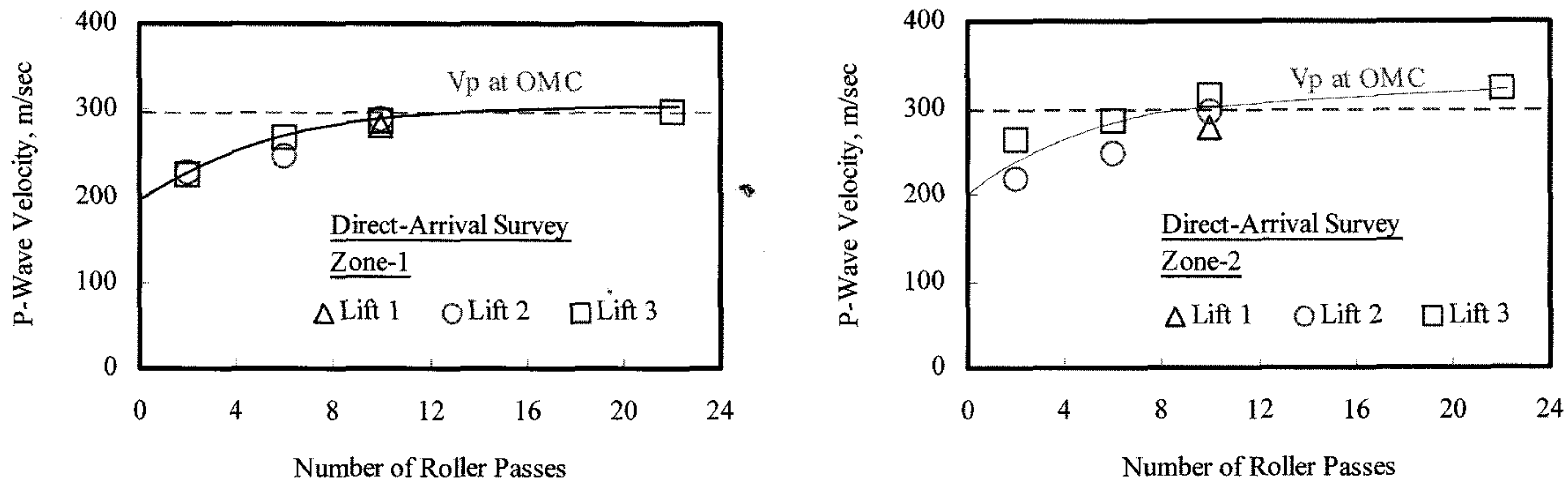


Fig. 10 P-wave Velocity Variation with No. of Roller Passes

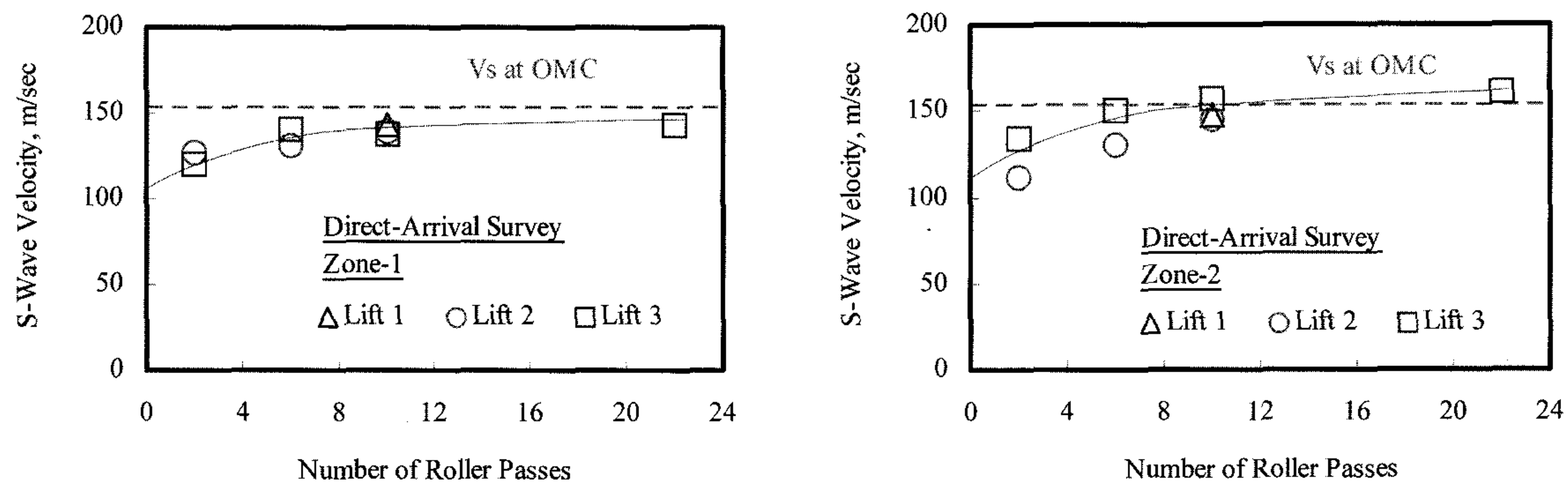


Fig. 11 S-wave Velocity Variation with No. of Roller Passes

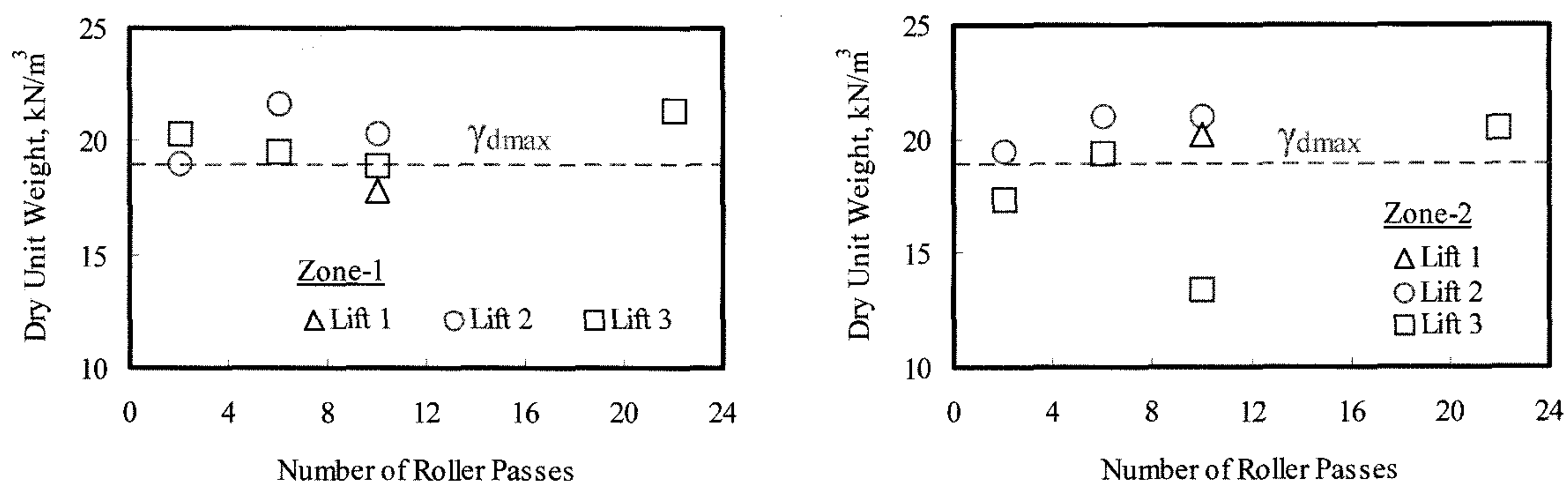


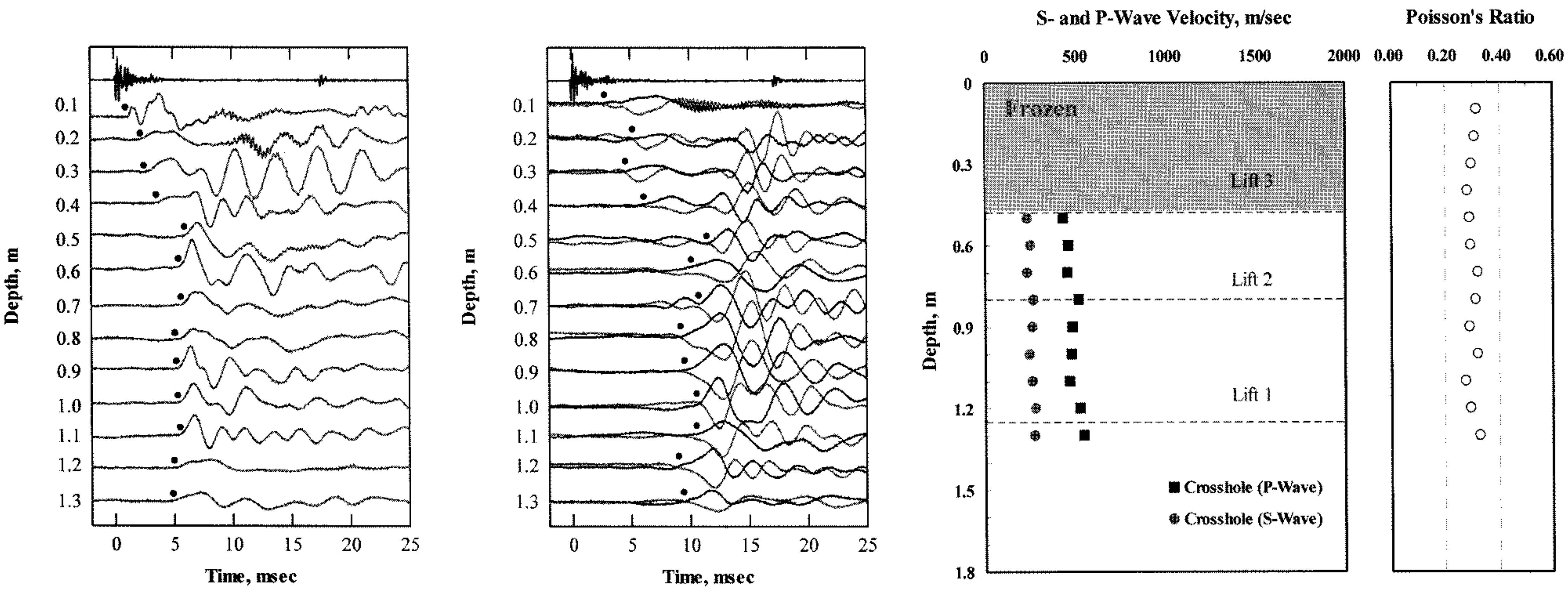
Fig. 12 Dry Density Variation with No. of Roller Passes

4.2 Field Density Measurement

To evaluate the performance of the field density as the control measure, field density measurements were carried out using sand cone method during roller passing. The values of specified number of roller passing were plotted along with maximum γ_d measured in laboratory as shown in Fig. 12. The measurement did not show any meaningful results. The field values fluctuate without any increasing trend with number of passes and some values already surpassed the target even at lower number of passes. This measurement appears to be simple and reliable method. But in reality the method seemed to heavily depend upon error-borne workmanship and rough field environment.

4.3 Crosshole Test

Upon the completion of fill, two uncased boreholes were drilled and cross-hole tests were performed to get the overall elastic wave velocity and Poisson's ratio profile and to compare with direct-arrival test results. The electro-mechanical source, recently developed by the authors, makes it possible to run cross-hole test with uncased boreholes [8]. The test was carried out every measurement depth of 10 cm and P-wave and S-wave signals are shown in Fig. 13, where dots indicate the first arrival times. The velocity profiles and Poisson's ratios are shown in Fig. 13(c). The top lift was frozen in sudden freezing weather and showed such an unexpected high velocity to the depth



(a) P-wave (b) S-wave (c) Elastic Wave Velocity and Poisson's Ratio Profiles

Fig. 13 Results of Crosshole Test

of 0.4m for sandy soil, which were left out in the following discussions. The lift 1 and 2 shows reasonable range of 430-550 m/sec and 230-280 m/sec for P-wave and S-wave velocities, respectively.

5. Comparison of Laboratory and Field Results

The field velocity includes the effect of confinement on the value, which should be eliminated so as to compare with laboratory or near-surface direct-arrival results. The field values were modified using Eq. 1 to the values under the mean effective stress of compaction mold, whose value is 1.635 kPa by taking the specimen height of 12.5 cm into account [9].

$$V_{modified} = V_{field}\left(\frac{\bar{\sigma}_{m,lab.}}{\bar{\sigma}_{m,field}}\right)^{n_V} \tag{1}$$

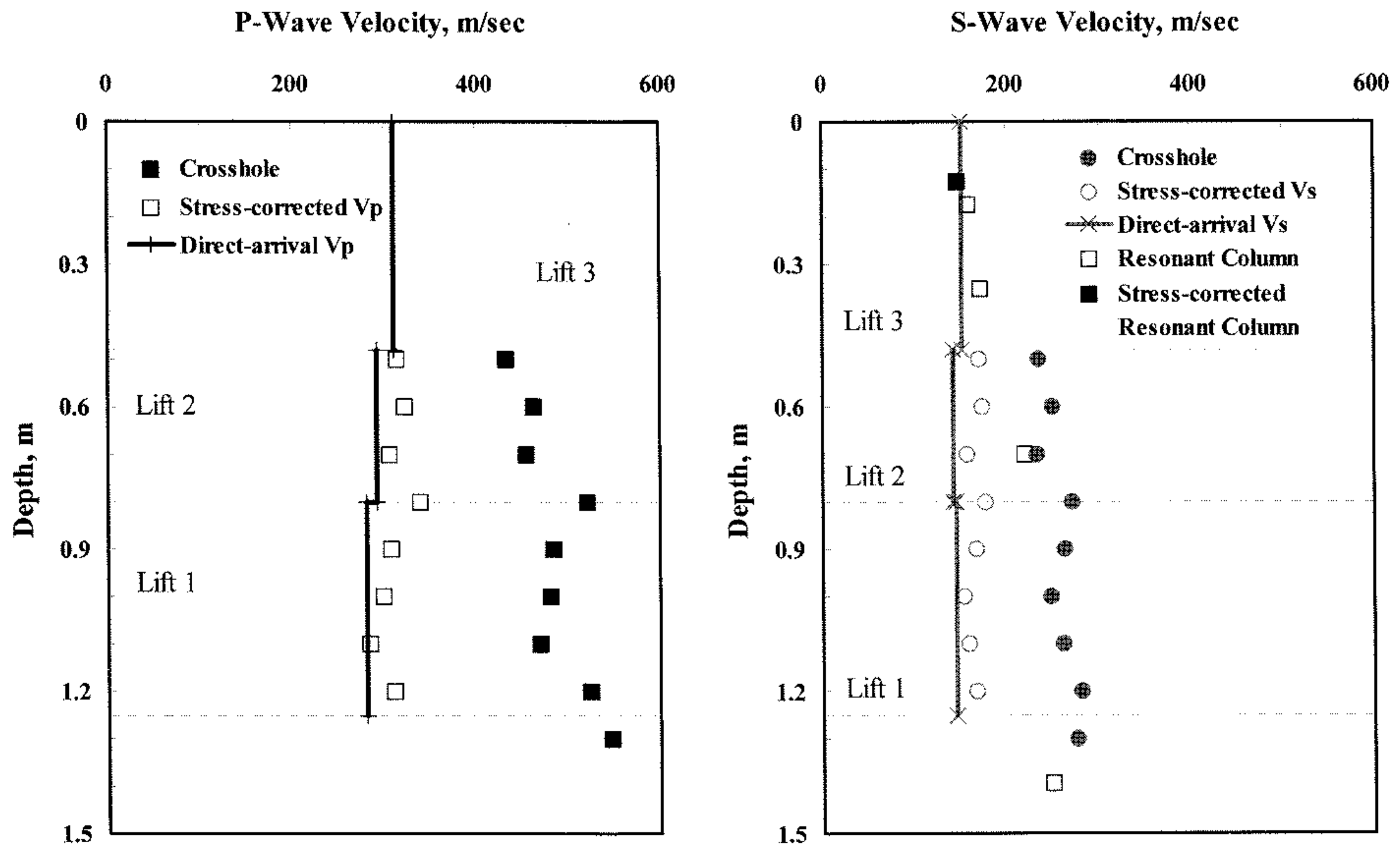
where, $\bar{\sigma}_{m,field}$: field mean effective stress at the measurement depth,

$\bar{\sigma}_{m,lab.}$: laboratory mean effective stress of compaction mold,

V_{field}: field velocity under field confinements,

$V_{modified}$: modified velocity to laboratory confinement,

n_V: coefficient of confining pressure, 0.23 mea-



(a) P-wave (b) S-wave

Fig. 14 Comparison of Modified Cross-hole Velocities with Direct-arrival Results

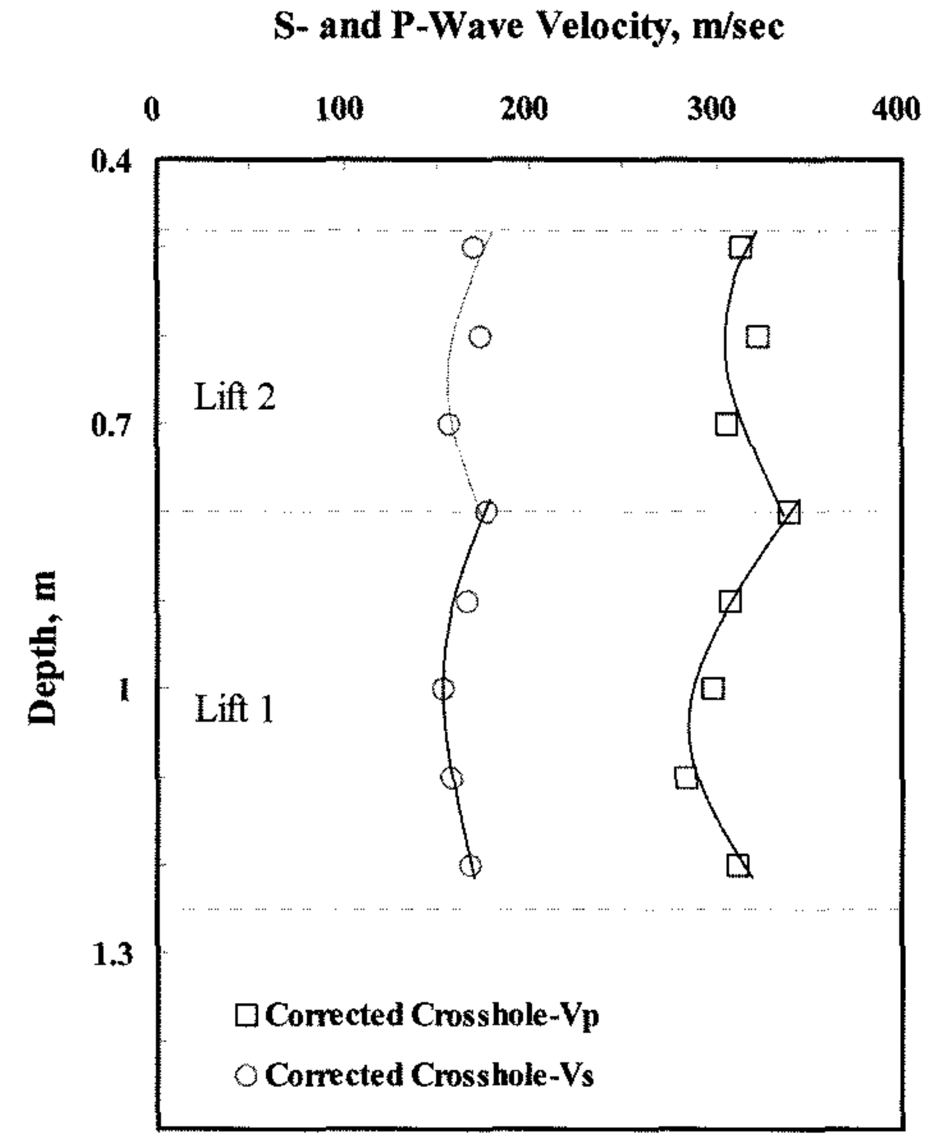


Fig. 15 Wave Velocity Variation within Each Lift

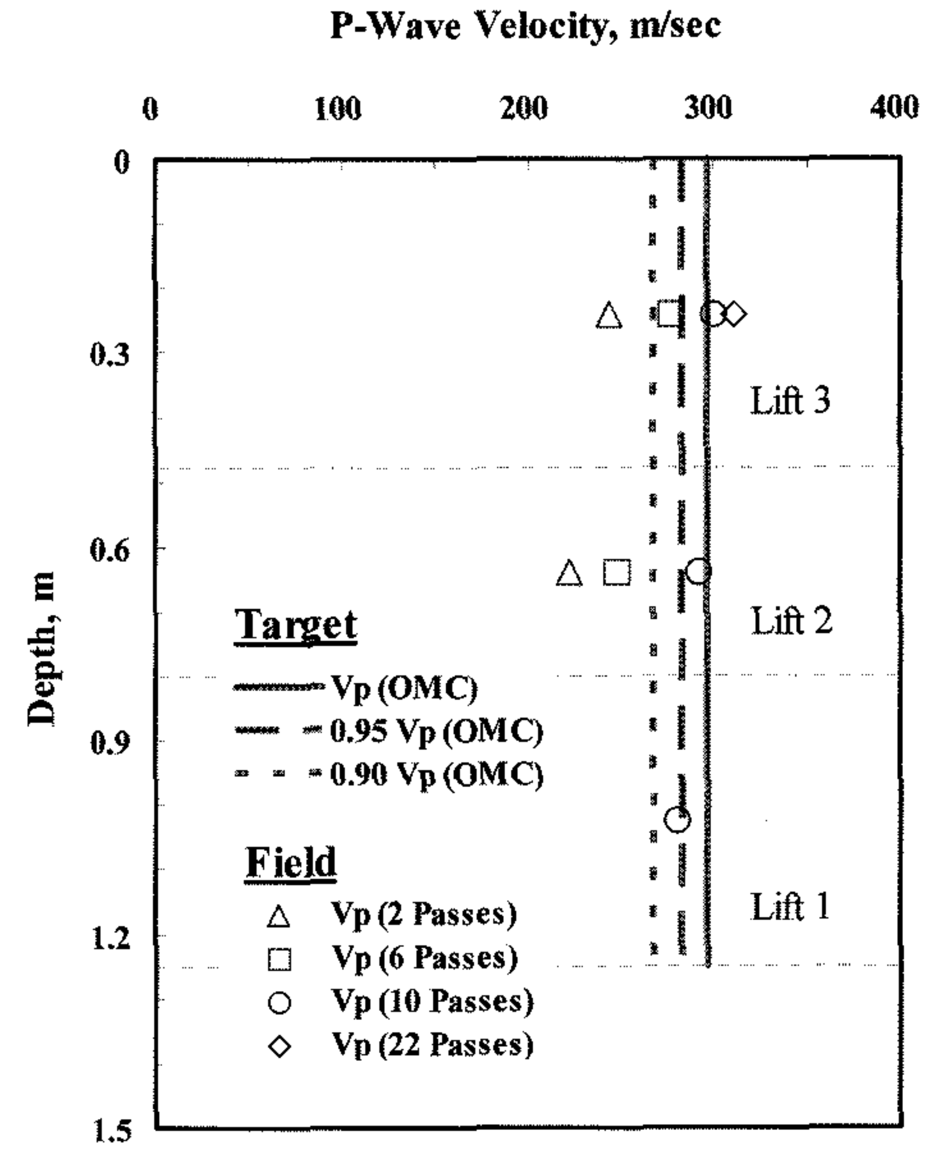


Fig. 16 Use of P-wave Velocity for Quality Control

sured by resonant column test.

The field and modified velocities were plotted in Fig. 14 along with direct-arrival results at 10 roller passes, which are considered to meet the target value. The modified cross-hole values are reasonably well agreed with the direct-arrival results. Resonant column test results also agree well with field cross-hole results. To look at closely the variation of velocity within the lift, the modified velocities were plotted again in Fig. 15. The velocity profile shows concave shape with higher value at lift boundaries and lower value in the middle. However, the minor degree of variation can be neglected and the velocity of each lift can be well represented by direct-arrival results. Thus, it can be concluded that P-wave velocity can be effectively used as quality control measure and direct-arrival method can be nicely fit to the implementation. The quality control can be achieved by comparing the P-wave velocities measured during field compaction with the target value determined in laboratory as shown in Fig. 16.

6. Proposing A Tentative Method

A new quality control method, in parallel with the advent of the new design procedure, is being proposed. This method is based upon P-wave velocity involving consistently the evaluation of design parameters in design stage, laboratory determination of target control value, and the field measurements during construction. The key concept of the method is that the target value for field compaction control is the P-wave velocity determined at OMC using modified compaction test, and direct-arrival method is used to measure the field values during construction. That is, the methodology follows exactly the same procedure as the density control, except the density being replaced by the P-wave velocity. A minor defect of the method is that P-wave velocity is much higher on the dry side of OMC than that of the wet side. Thus, field compaction water content of OMC±2% should be supplemented in the specification, to prohibit contractors from taking advantage of higher modulus at the dry side of the optimum. The procedure is proposed as follows and as shown in Fig. 17:

(1) Follow the procedure of the conventional compaction test and measure p-wave velocity with each compaction mold.

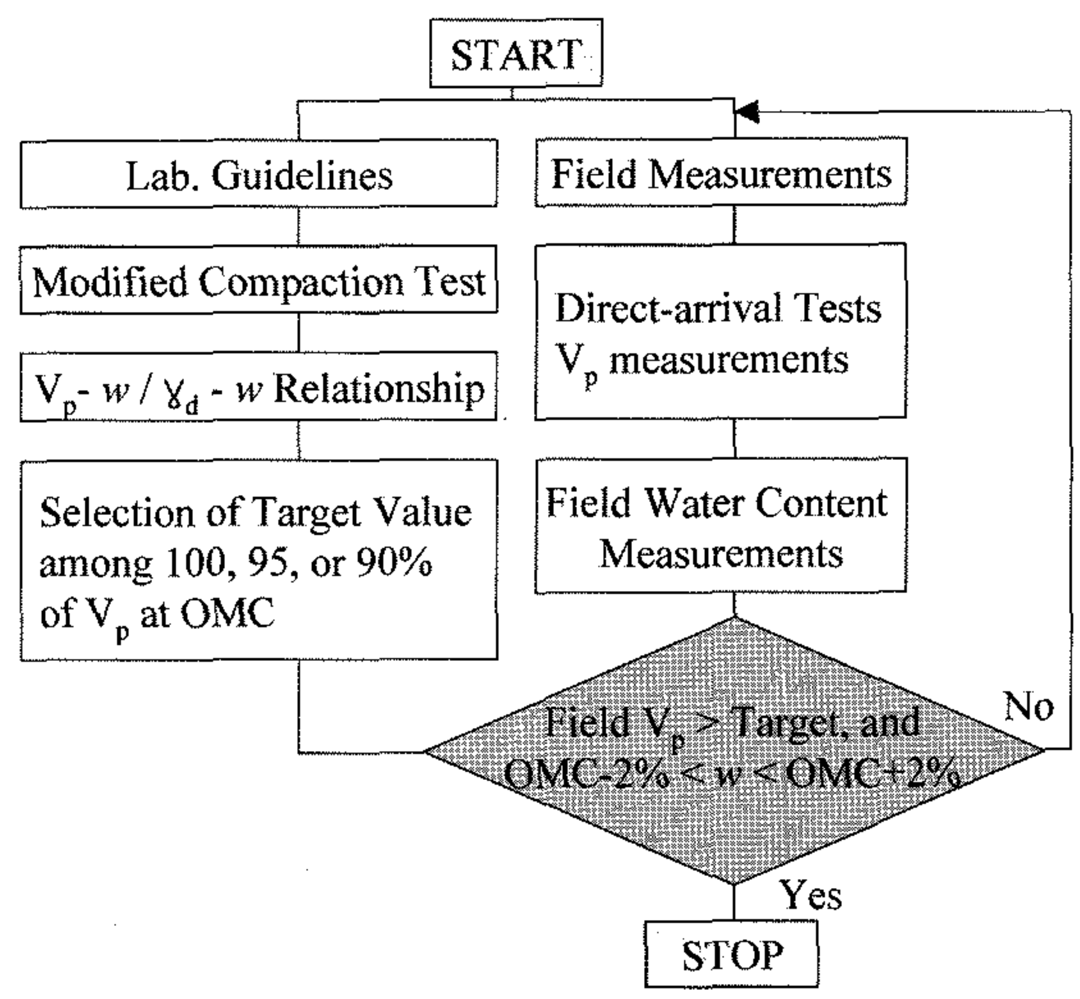


Fig. 17 Procedure for Quality Control

(2) Determine the target P-wave velocity at OMC and also specify the field compaction water content as OMC±2%.
(3) Run direct-arrival test to measure field P-wave velocity of each lift with increasing number of roller passes and also measure field water content.
(4) Compare the field value with the target.
(5) Keep step 3 and 4 until field value meets the target.

7. Conclusions

To develop a new quality control method for track-bed fills, P-wave velocity was adopted as the control measure. The methodology follows exactly the same procedure as the density control, except the density being replaced by the P-wave velocity. The propose method was verified at a test site and the following conclusions are drawn:

(1) P-wave velocity is an excellent measure for quality control for track-bed fills both in the theoretical and practical point of view. P-wave velocity is more closely related with key design parameter (resilient modulus) and less error-borne in field measurements than density.
(2) The target value (P-wave velocity at OMC) can be easily determined in laboratory with minor modification of conventional compaction test.
(3) Direct-arrival method works well for the determination of field P-wave velocity. The method is technically simple and costly accessible enough for practice engineers to use with easy.
(4) A minor defect of the method is that P-wave velocity is much higher on the dry side of OMC than that of the wet side. Thus, field compaction water content of OMC±2% should be supplemented in the specification, to prohibit contractors from taking advantage of higher modulus at the dry side of the optimum.

Acknoledgements

This research was supported by a grant (C105B1000 008-07B010000612) from Research Policy & Infrastructure Development Program (RPIDP) funded by Ministry of Land, Transport and Maritime Affairs of Korean government.

Reference

1. Korea Rail Network Authority (2004). Design criteria for railroad (Roadbed) (in Korean).
2. Korea Train Express (2006). Specification for high speed railway construction (Roadbed), 780p. (in Korean).
3. Korea Railroad Research Institute (2006). The research of design criteria for the optimum track foundation thickness, Report No. R&D 05-08 (in Korean).
4. Park, C. S., Choi, C. Y., Choi, C. L., and Mok, Y. J. (2008a). Resilient moduli of sub-ballast and subgrade materials. Journal of the Korean Society for Railway, Vol. 11, No. 1, 54-60 (in Korean).
5. Park, C. S., Park, I. B., Kim, H. S., Choi, C. Y., and Mok, Y. J. (2008b). Preliminary investigation for quality control of railroad compaction fills using stiffness measurements. Spring Conference of the Korea Society for Railway (CD-ROM), 12-13, Jun, 2008 (in Korean).
6. D'Appolonia, D. J., Whitman, R. V., and D'Appolonia, E. D. (1969). Sand compaction with vibratory roller. Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 95, No. SM1, 263-284.
7. Richart, F. E., Jr., Hall, J. R., Jr., and Wood, R. D. (1970). Vibration of soils and foundations, Englewood Cliffs, New Jersey, Prentice-Hall Inc.
8. Mok, Y. J. and Park, C. S. (2007). Determination of shear wave velocities of soil fills using in-hole seismic method. Proceedings of KSCE Conference, Daegu EXCO, Oct., 2007, 3502-3505 (in Korean).
9. Tokimatsu, K. and Uchida, A. (1990). Correlation between liquefaction resistance and shear wave velocity. Soils and Foundations, JSSMFE, Vol. 30, No. 2, 33-42.