Rising Experiment of Slip Form System Using Surface Wave Velocity

Hee Seok Kim, Young Jin Kim, Won Jong Chin, and Hyejin Yoon

***Abstract*—The economic efficiency of the slip form system depends on the careful maintenance of the adequate lifting speed enabling to satisfy the construction quality required on site. This lifting rate is determined with respect to the extent of setting of concrete. This study intends to measure the extent of hardening of concrete placed inside the slip form system using the surface wave. The wavelet transform is adopted for the analysis of the surface wave. Numerical analysis is then conducted to determine the appropriate position of the probe for the measurement of the surface wave. Moreover, the surface wave velocity is measured according to the hardening degree of concrete by performing penetration resistance test, compressive strength test and surface wave velocity measurement test with respect to the mix proportions and curing temperature of concrete. This process enabled us to determine the surface wave velocity necessary for the rise of the slip form system. The validity of the surface wave velocity determined in this study as a criterion for the lifting of the slip form system is finally established by means of a mockup test.**

***Index Terms*—Slip form system, setting of concrete, surface wave velocity, wavelet transform.**

I. INTRODUCTION

The economic efficiency of the slip form system depends on the careful maintenance of the adequate lifting speed enabling to satisfy the construction quality required on site. The design lifting speed of the slip form system must be determined under sufficient consideration of the type of cement and admixtures, the height of the slip form and, the capacity of the jacking device. The actual rise speed of the slip form system during the erection must be set in advance in order to secure safety and construction quality and, must be smaller than the design speed. However, the actual lifting speed must be determined with respect to the degree of hardening of concrete placed on site even if the design speed has been decided. This requirement is primordial since problems in the safety of the slip form system and in the quality control of the concrete surface can be encountered because concrete will fail to develop sufficient strength by flowing out or will be deformed if concrete becomes exposed out of the slip form before achieving curing with the appropriate strength. In addition, if stripping from the slip form is conducted after excessive curing of concrete, problems in the construction quality will occur due to the formation of construction joints or loss of safety may be encountered following the need of excessive jacking force to lift the slip form system due to the bonding between concrete and the form. Accordingly, the rise of the slip form system shall be performed at the time at which concrete can be self-supported at the removal of the form and can develop sufficient strength in a long-term. Moreover, lifting shall be done before excessive jacking force is required to overcome the bond between concrete and the form.

Here, the eventual self-support capacity of concrete can be evaluated by means of the measurement of the initial setting time through penetration resistance test. The extent of bonding and the capacity of concrete to develop sufficient strength in a long-term can be evaluated by compressive strength test [1]. Following, this study performs concurrently surface wave measurement test, penetration resistance test [2], and compressive strength test [3] so as to identify the relationship between the surface wave velocity, the initial setting time and the compressive strength of concrete. The continuous wavelet transform is adopted to measure the surface wave velocity [4], and the adequate positions of the probes for measuring the surface wave velocity is determined by numerical analysis.

As a result, the surface wave velocity for the rise of the slip form system is suggested and applied for the determination of the rising time of the slip form system in a mockup test to validate its applicability.

II. REMOVAL STRENGTH OF SLIP FORM

The stripping criterion for the slip form system proposed by the ACI Committee 347 [5] recommends that "the experienced technician must verify the sufficient hardening of concrete inside the slip form using a penetration cone so as to prevent the occurrence of construction joints or delamination of concrete considering the varying conditions on site." Accordingly, most of the sites using the slip form system in Korea lift the slip forms by relying on indirect criteria based on penetration test [2] or the skilled experience of the technicians who introduce a steel reinforcement in concrete rather than on explicit criteria related to the stripping strength of concrete.

Through a more systematic study, Reichverger and Jaegermann [1] suggested appropriate removal strengths of the slip form by means of various tests under the assumptions that "the concrete placed in the form must be sufficiently fresh for easy shifting of the form, the concrete exposed outside the form must have sufficient strength to resist the pressure of the overlying concrete without any damage, and the surface of the casting must be amenable to floating after stripping considering the construction quality." Based upon experimental results, these authors reported that, for stripping at strength of about 0.2 to 0.3 MPa, concrete experienced small deformation, developed 100% of its strength at 28 days, and offered easy surface

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treatment for the management of construction quality. However, the application of such stripping strength criterion requires the compressive strength data for all concretes placed continuously. Determining the rising time of the slip form is thus nearly impossible by measuring the compressive strength of the casting at each placing.

Accordingly, this study develops a system attached to the slip form system and enabling continuous measurement of the surface wave velocity during the erection. The relationships between the surface wave velocity, penetration resistance and compressive strength are derived so as to exploit the surface wave velocity for the determination of the rise time of the slip form system.

III. Determination of the Position of the Probe for the Measurement of the Surface Wave Velocity

The vibration generated by hitting the surface of a medium propagates in the medium in the form of compression wave (P-wave), shear wave (S-wave) and surface wave (R-wave) at respective ratios of about 7%, 26% and 67% with respect to the total energy [6]. The compression and shear waves propagate radially in the medium and, generate reflected waves due to the presence of the aggregates, reinforcement or the thickness of the structure when produced at the surface of a reinforced concrete structure. At that time, mode conversion occurs at the reflection plane making the so-produced mix of reflected compressive and shear waves propagate inside the structure. Therefore, the application of the compression and shear waves appears to be difficult when the thickness to be penetrated by the ultrasonic wave is large like pylons. The difficulty worsens in case of structures including reflectors like steel reinforcement. Besides, the surface wave experiences rapid attenuation as much as the distance from the surface increases. In the case of a surface wave generated at the surface of a concrete structure, since the surface wave propagates along the surface without interference of the reinforcement in the core or the thickness of the structure, no problem like mode conversion will occur. Therefore, the surface wave can be applied effectively in structures for which the hardening characteristics of concrete at the surface is important such as structures erected by the slip form system.

In order to identify the exact arrival time of the surface wave, this study adopts the wavelet transform technique proposed by Shin et al. [4]. Shin et al. performed surface wave tests and numerical analyses by fixing the position of the first receiver at 50 mm from the vibration source and varying the position of the second probe. This setup was conceived to ease the measurement of the surface wave by considering the position at which sufficient separation of the compression wave, shear wave and surface wave from the generated ultrasonic wave. However, since this position depends significantly on the contact time of the source of the ultrasonic wave, need is to find out the optimal position of the probe normalized with respect to the contact time in order to apply this technique to the slip form system.

TABLE I: Material Properties for Numerical Analysis

Elastic modulus (N/m^2)	Poisson's ratio	Density (kg/m^3)
34×10^9	0.22	2400

Accordingly, this study conducts numerical analysis for measuring the surface wave with respect to the position of the probe and vibration source to find out the optimal position of the probe. Fig. 1- Fig. 3 describes respectively the numerical model, the 2 degrees-of-freedom element, and the loading curve adopted in this study. Table I arranges the material properties used in the numerical analysis. In Fig. 1, the paraxial boundaries are one kind of absorbing boundary condition for removing the reflected waves at the boundaries in the numerical analysis [7], [8]. The removal of the reflected waves at the boundaries enables to use a lesser number of elements so as to improve the effectiveness of the analysis of the wave propagation problem. However, despite of their outstanding performance, the boundary conditions are constituted by partial differential equations, which make their application difficult for finite element analysis. In this study, the paraxial boundary conditions are applied in the finite element analysis by means of the functional proposed by Kim *et al.*, [9]. The averaged acceleration method is adopted as implicit method for the time integration considering an integration time interval of 1 μsec to perform the analysis up to 140 μsec.

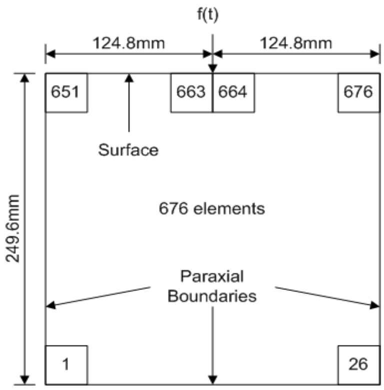

Fig. 1. Numerical model.

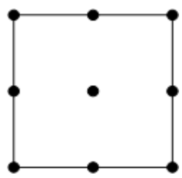
Fig. 2. 9-node equivalent parametric element.

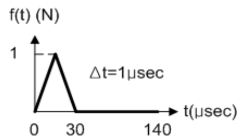

Fig. 3. Loading curve.

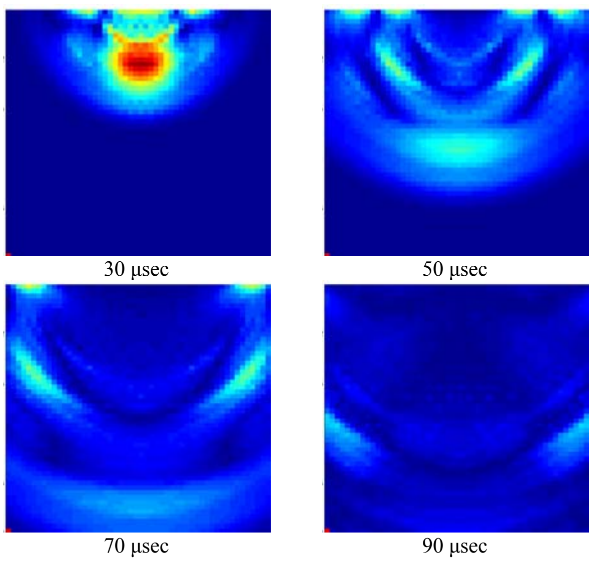

Fig. 4. Propagation of stress wave.

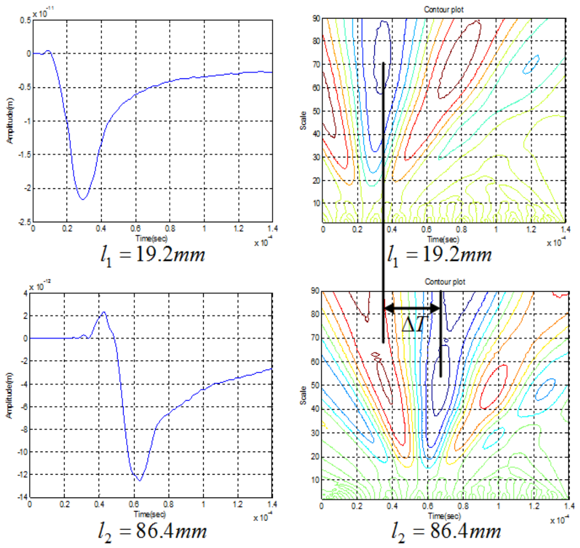

Fig. 5. Signals at the probes and corresponding CWT.

Fig. 4 shows the propagation of the stress wave with time obtained by numerical analysis of the progression of the elastic wave. The propagation of the surface wave of which energy is concentrated at the surface can be observed. In addition, the outflow of the stress wave can also be observed without reflected wave at the left, right and bottom sides.

In Fig. 5, the two images on the left side show the signal measured at the probes located on the surface at respective distances of 19.2 mm (l_1) and 86.4 mm (l_2) from the forcing point and, the two images on the right side plot the values of continuous wavelet transform (CWT) corresponding to the images on the left side.

Equation (1) formulates the continuous wavelet transform used to obtain the value of CWT in Fig. 5. Equation (2) expresses the mother wavelet of Morlet used in Equation (1). In Equation (1), $g(t)$ is the input signal, a is the compression coefficient and, b is the transfer coefficient.

$$W(b,a)=\frac{1}{\sqrt{a}}\int_{-\infty}^{\infty} g(t)\,\psi\left(\frac{t-b}{a}\right)dt \tag{1}$$

$$\psi(t)=\exp\left(-\frac{t^2}{2}\right)\cos(5t) \tag{2}$$

As explained above, the surface wave propagates with the largest energy (±67%). Therefore, the points with the largest values in the CWT of Fig. 5 can be estimated by means of the times at which the surface wave passes through the points at l_1 and l_2. Accordingly, the velocity of the surface wave can be obtained using Equation (3) by dividing the distance between the two probes (l_2–l_1) by the time difference (ΔT) between the points at l_1 and l_2.

$$V_R=\frac{l_2-l_1}{\Delta T} \tag{3}$$

$$\left(2-\frac{V_R^2}{V_S^2}\right)^2-4\left(1-\frac{V_S^2}{V_P^2}\frac{V_R^2}{V_S^2}\right)^{1/2}\left(1-\frac{V_R^2}{V_S^2}\right)^{1/2}=0 \tag{4}$$

$$\lambda_R=V_R\times T \tag{5}$$

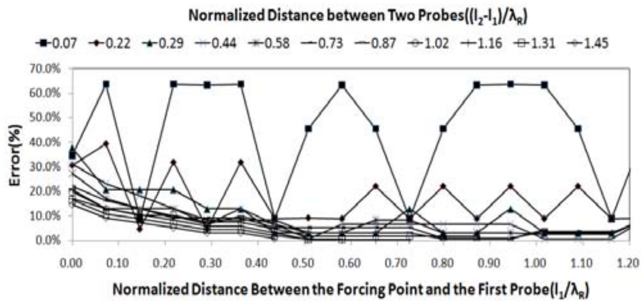

Fig. 6. Error according to the distance between the vibration source and first probe.

Equation (4) is the characteristic equation for the surface wave velocity computed by introducing the potential related to the compression and shear waves propagating along the surface in the traction boundary conditions at the surface [10]. In Equation (4), V_P, V_S and V_R are the respective velocities of the compression, shear and surface waves. Fig. 6 plots the error between the surface wave velocity computed by Equations (1) to (3) and the surface wave velocity computed by the analytic solution of Equation (4). All the distances are normalized by division the distance by the wave length of the surface wave in Equation (5). In Equation (5), T represents the period of 1 wave length of the surface wave. A value of 30 µsec is applied for the contact time in the numerical analysis of this study.

In Fig. 6, excessive error occurs regardless of the distance to the forcing point when the distance between the two probes is larger than 0.07 times the wave length of the surface wave. This error can be explained by the erroneous measurement of the arrival time of the surface wave at each of the probes in the continuous wavelet transform because of the excessively shorter distance between the two probes compared to the wave length of the surface wave. However, the error between the surface wave velocity obtained by numerical analysis and the analytic value obtained by the characteristic equation drops below approximately 10% when the distance between the forcing point and the first probe is larger than 0.3 times the wave length of the surface wave and when the distance between the two probes is longer than 0.3 times the wave length of the surface wave. Accordingly, the surface wave velocity can be estimated by Equations (1) to (3) with an error smaller than 10% if the distance between the two probes and the distance between the forcing point and the first probe are maintained to be larger than about 0.3 times the wave length of the surface wave.

IV. Determination of Surface Wave Velocity for the Stripping of the Slip Form System

TABLE II: Mix Proportions of Concrete

	MIX 1 (OPC)	MIX 2 (SC)
Characteristics	20-40-200	20-400-200
W/C (%)	35.4	35.4
Water (kg)	168	168
Cement (kg)	475	475
Sand (kg)	760	760
Aggregate (kg)	935	935
AE water reducing agent (kg)	4.75	4.75

Surface wave velocity measurement test, penetration resistance test and compressive strength test were performed considering two concrete mixes and five curing temperatures (5°C, 15°C, 20°C, 30°C, 35°C) to derive the relationship existing between the surface wave velocity, penetration resistance and compressive strength. Table II arranges the mix proportions of the 2 concrete mixes adopted in this study. MIX 1 is the ordinary Portland cement (OPC) mix, and MIX 2 is the slag cement (SC) mix.

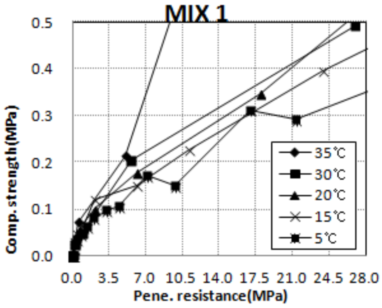

Fig. 7(a). Penetration resistance and compressive strength (MIX 1).

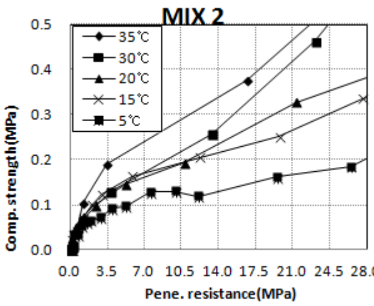

Fig. 7(b). Penetration resistance and compressive strength (MIX 2).

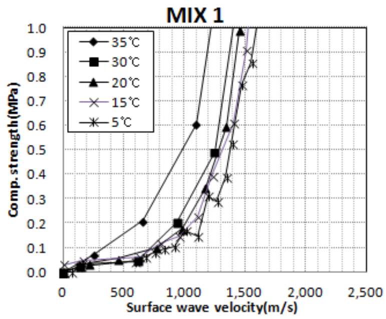

Fig. 8(a). Surface wave velocity and compressive strength (MIX 1).

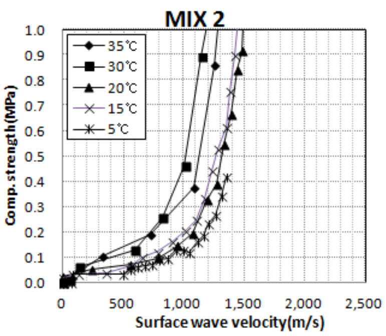

Fig. 8(b). Surface wave velocity and compressive strength (MIX 2).

Fig. 7(a) and (b) present the relation between the penetration resistance and the compressive strength for MIX 1 and MIX 2. The compressive strength corresponding to the penetration resistance of 3.5 MPa (initial setting time) is seen to be lower than 0.2 MPa in all cases whatever the curing temperature and concrete mix conditions. This indicates that the compressive strength criterion is more conservative than the penetration resistance criterion. Following, it seems acceptable to set the surface wave velocity corresponding to the compressive strength of 0.2 MPa as the criterion for the rise of the slip form.

Fig. 8(a) and Fig. (b) present the relation between the surface wave velocity and the compressive strength for MIX 1 and MIX 2. The surface wave velocity corresponding to the stripping strength (larger than 0.2 MPa) suggested by Reichverger and Jaegermann [1] is seen to range between about 600 m/s and 1300 m/s. Accordingly, it can be stated that the slip form system shall be risen with respect to the surface wave velocities of Fig. 8 according to the concrete mix and curing temperature conditions.

V. Rising Experiment of Slip Form System Using Surface Wave Velocity

In this experiment, the slip form system is lifted with respect to the surface wave velocity of 1100 m/s using the slag cement mix (MIX 2). The surface wave velocity of 1100 m/s was computed from Fig. 8(b) considering the concrete mix (MIX 2) and the curing temperature (15°C). This mockup test was planned for the erection of a rectangular hollow concrete pylon with a height of 10 m exhibiting a tapered section varying from 4.00 m×4.00 m at the base to 3.77 m×3.60 m at the top. A surface wave velocity measurement equipment was developed (Fig. 9(a)) and inserted in the bottom of the form (Fig. 9(b)) to measure the surface wave velocity.

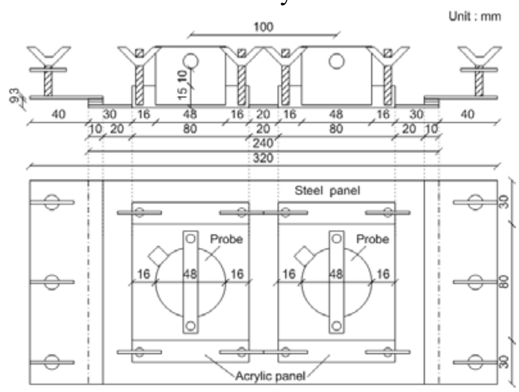

Fig. 9(a). Surface wave velocity measurement device.

Fig. 9(b). Surface wave velocity measurement device inserted in the bottom of the form.

Fig. 10. Slip form system.

The surface wave velocity measurement equipment inserted in the bottom of the form was installed at the base of the slip form system as shown in Fig. 10. The equipment was disposed on the 4 sides of the slip form system so as to be able to measure the surface wave velocity on all the sections of the pylon.

Concrete was placed at a rate of 25 cm at intervals of 2 hours. The slip form system was risen in both cases where the surface wave velocity was smaller and larger than 1100 m/s.

Fig. 11 illustrates the surface wave analysis program KSWIS v4.0 designed to analyze the surface wave velocity using the signals measured on the 4 sides of the slip form system. KSWIS v4.0 can control remotely the ultrasonic emitter and receiver as well as the data transmission device. The program is also designed to analyze simultaneously the surface wave signal from 6 ultrasonic wave signals.

Fig. 12(a) plots the variation of the surface wave velocity measured by the measurement equipment shown in Fig. 10. Fig. 12(b) plots the variation of the surface wave velocity measured by the measurement equipment installed on the face opposite to that shown in Fig. 10. In Fig. 12, it can be observed that the surface wave velocity experiences sudden reduction after having reached a definite value. This can be explained by the fact that the surface wave velocity was measured when the surface wave measurement equipment of Fig. 10 reached the concrete placed relatively later due to the lifting of the slip form system. It can also be seen that the measurement of the surface wave velocity was not done from 12:00 of the 6th day to 21:00 of the 7th day. This blank is due to the interruption of the slip form system caused by the dysfunction of the spindles necessary to control the tapered section of the slip form system. The parts highlighted by the arrows in Fig. 12 indicate the periods at which the surface wave velocity experienced sudden drop. These periods correspond also to the rising time of the slip form system. This explains the exact correspondence of these parts in Figs. 12(a) and (b). However, some arrows of Fig. 12(a) are absent in Fig. 12(b) and vice versa. Such discordance is due to the lack of precision in the measurement of the surface wave velocity caused by the deficient bonding between the surface wave velocity measurement equipment and the surface of concrete.

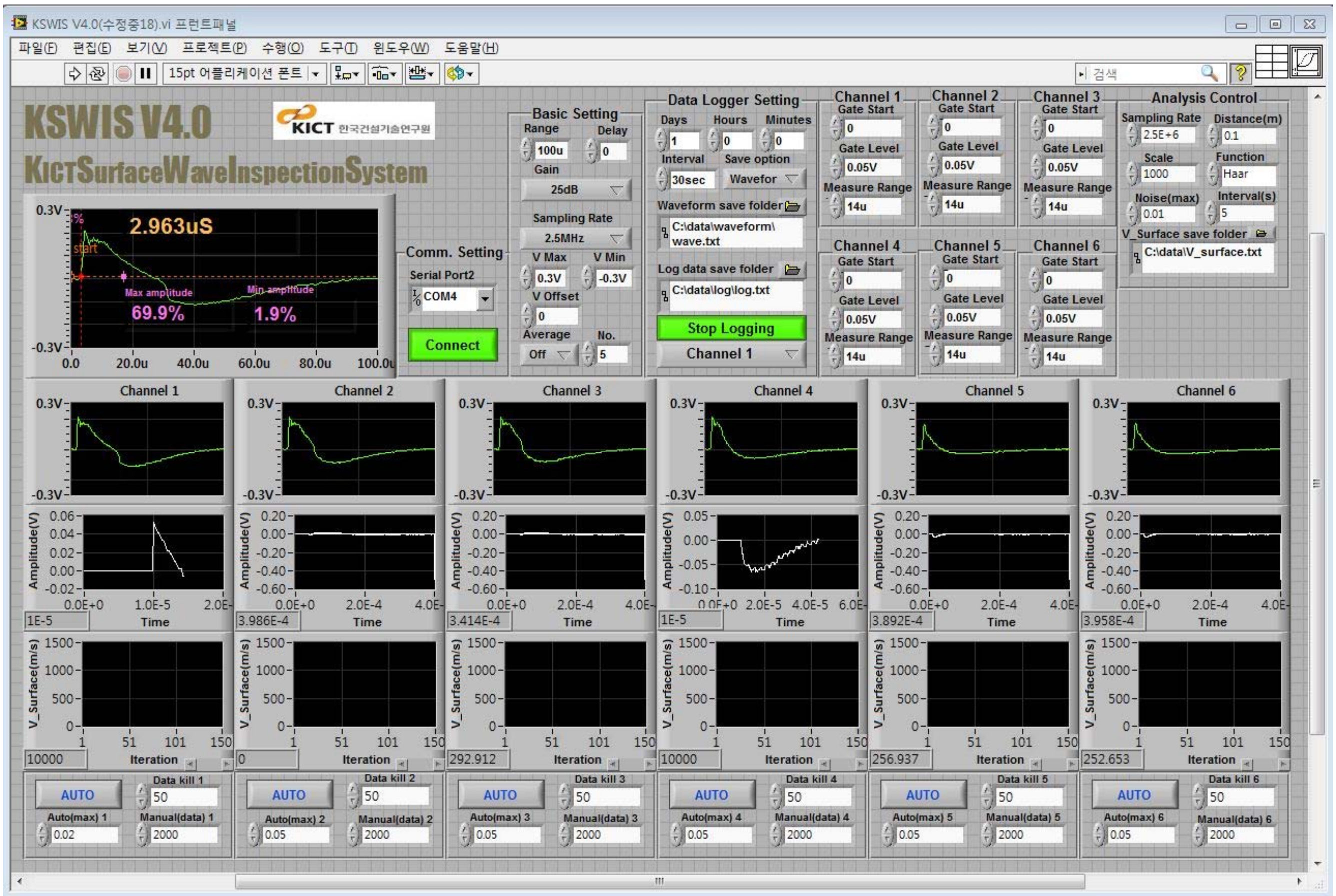

Fig. 11. Surface wave analysis program (KSWIS v4.0).

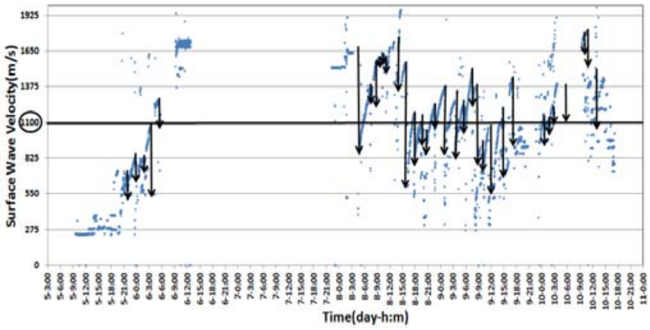

Fig. 12(a). Variation of the surface wave velocity.

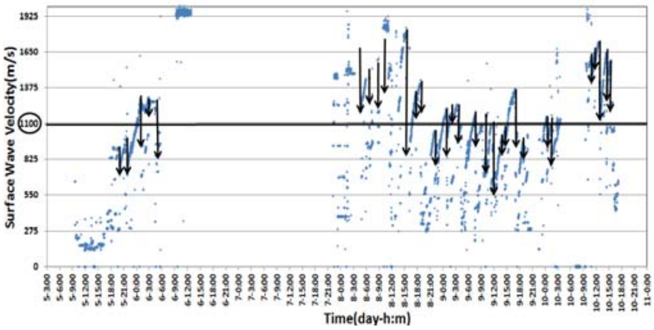

Fig. 12(b). Variation of the surface wave velocity.

Fig. 13(a). Surface of concrete (surface wave velocity<1100 m/s).

Fig. 13(b). Surface of concrete (surface wave velocity>1100 m/s).

Fig. 13(a) pictures the surface of exposed concrete when the lifting of the slip form system was executed before the surface wave velocity reached 1100 m/s. Fig. 13(b) shows the surface of exposed concrete when the lifting of the slip form system was executed after the surface wave velocity reached 1100 m/s. In Fig. 13(a), the surface of concrete is irregular and local delamination can also be observed. Besides, no problem can be observed on the surface of concrete in Fig. 13(b).

Fig. 14. Completed concrete pylon with tapered section.

Fig. 14 shows the completed concrete pylon with tapered section. The rise of the slip form system up to a height of 10 m with respect to the surface wave velocity resulted in satisfactory surface of concrete in all the portions erected with a surface velocity larger than 1100 m/s. Accordingly, the surface wave velocity established in this study can be exploited as criterion for the rise of the slip form system.

VI. CONCLUSIONS

This study investigated the possibility to use the surface wave for measuring the extent of hardening of concrete placed in the slip form system. Penetration resistance test, compressive strength test and surface wave velocity measurement test were carried out considering two types of concrete mix and 5 curing temperatures. The results enabled us to propose the surface wave velocity required for the rise of the slip form system. A mockup test was performed successfully through the erection of a concrete pylon with tapered section using the proposed surface wave velocity. This experiment demonstrated the applicability of the proposed surface wave velocity as criterion for the rise of the slip form system. However, further studies shall improve the surface wave velocity measurement equipment and its bond with the surface of concrete to achieve more accurate measurement of the surface wave velocity. In addition, the developed surface wave analysis program KSWIS v4.0 shall also be improved by adding a noise removal function. Finally, need is also to secure standard surface wave velocities for the rise of the slip form system through surface wave velocity measurement tests on diversified concrete mixes and curing temperatures.

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