한국해양공학회지 제16권 제1호, pp 52~57, 2002 (ISSN 1225-0767)

Upheaval Buckling of Offshore Pipelines due to the Transportation of High Pressure and High Temperature Liquid

HYUN-MO SON*, SI-YOUNG KIM* and HAN-SUK CHOI**
*Pukyong National University, **Pusan National University, Busan, Korea

고온 고압의 유체 수송에 의한 해저 파이프의 수직 좌굴 현상

*손현모, *김시영, **최한석
*부경대학교 제어기계공학과, **부산대학교 조선해양공학과

KEY WORDS: Transportation 수송, High Pressure and high Temperature Liquid 고온고압 유체, Upheaval Buckling 수직 좌굴 현상, Offshore Pipelines 해저 파이프, Safety Factor 안전계수, Initial Imperfection 초기융기

요 약: *본 논문은 고온 고압의 유체를 수송하는 해저 파이프의 좌굴 현상에 대해서 논하였다. 고온 고압의 유체를 해저 파이프로 수송 할 때, 수송되는 고온 고압의 유체와 주위 해저의 온도와 압력들의 차에 의해서 유체 수송 파이프는 축 방향으로 압축력을 받게 되고 이 압축력을 견디지 못하면 수송 파이프는 수직 방향의 좌굴 현상이 발생하게 된다. 논문에서는 "semi-empirical design method"를 사용하여 수송 유체의 온도와 압력의 여러 가지 변화에 따라 파이프의 축 방향 압축력을 계산하고 수직 좌굴 현상에 따른 안전계수를 구하여 파이프의 초기 설계 결정에 도움을 주고자 했다.*

1. Introduction

When a buried pipeline is operated at a temperature and pressure higher than ambient temperature and pressure, it tends to expand. If the pipeline is not free to expand, it would develop an axial compressive force.

The buried pipeline will bend toward the uplift at a certain location since the pipeline is assumed to have an infinite resistance at horizontal and downward directions. This phenomenon is called an upheaval buckling and usually occurs at the locations of initial pipe imperfections, which are commonly caused during the installation of offshore pipelines. If the force exerted by the pipe on the soil exceeds the vertical restraint against the uplift capacity created by the submerged weight of the pipe and soil resistance, the pipeline tends to develop an upheaval buckling. The possibility of upheaval bucklings has become of great concern to the pipeline industry, as production temperature has risen. Thus, various analysis methods have been developed to investigate and resolve the upheaval buckling problems. The present paper describes the upheaval bucking and the relationship among the axial compressive forces, the safety factors, temperature and pressure. A semi-empirical simplified method was used for a preliminary design of offshore pipelines.

제1저자 손현모 연락처: 부산시 해운대구 좌동 1398번지
엘지 아파트 124동 502호
051-701-9348 sonny53@netian.com

2. Simplified Method

For the initial design of a pipeline, the following simplified method is used to check the safety factor against the upheaval buckling. The simplified method assumes that the profile of the pipeline is sinusoidal and the pipe deflection is within the elastic limit after the upheaval buckling. This method does not consider the horizontal sliding and plastic deformation of the pipeline during the upheaval buckling. If the safety factor is not enough, then the accurate FE method should be implemented. The simplified method can be used for a preliminary design of the pipelines. The stability of the pipeline in its initial position varies depending on both the local profile of the pipe in contact with its foundation and whether or not enough downward force is present to hold the pipe in position. If the pipe does not move, the governing factors are the constrained axial force and the pipe flexural rigidity. An arbitrary pipeline profile can be defined by a height y and a horizontal distance x. The pipeline is idealized as an elastic beam, which carries an axial compressive force P and has flexural rigidity. From the elementary beam-column theory that the downward force *w(x)* per unit length required to maintain the pipeline in equilibrium is:

$$w(x) = -EI \cdot \frac{d^4 y}{dx^4} - P \cdot \frac{d^2 y}{dx^2} \qquad (1)$$

Assume a simple sinusoidal profile of the upheaval buckling is defined by

$$y = d \cdot \cos^2\left(\frac{\pi x}{L}\right) \cdot \text{ in } \cdot -\frac{1}{2}L < \pi < \frac{1}{2}L \qquad (2)$$

where d is the height of the profile imperfection L and is the length of the imperfection along the pipeline.

Substitute the second and forth derivatives with respect to x into Equation (1), the downward force required is:

$$w(x) = \left\{2 \cdot d \cdot P \cdot \left(\frac{\pi}{L}\right)^2 - 8 \cdot d \cdot EI \cdot \left(\frac{\pi}{L}\right)^4\right\} \cdot \cos\left(\frac{2\pi x}{L}\right) \cdots\cdots (3) \qquad (3)$$

The maximum value occurs at the crest of imperfection (x = 0) such that

$$w(x) = 2 \cdot d \cdot P \cdot \left(\frac{\pi}{L}\right)^2 - 8 \cdot d \cdot EI \cdot \left(\frac{\pi}{L}\right)^4 \qquad (4)$$

The Equation (4) applies to a particular profile shape, but the specific shape only affects the coefficients and not the general form of the equation.

A dimensionless maximum download parameter Φ_w can be defined by:

$$\Phi_w = \frac{w \cdot EI}{d \cdot P^2} \qquad (5)$$

A dimensionless imperfection length Φ_L can be defined by:

$$\Phi_L = L \cdot \left(\frac{P}{EI}\right)^{\frac{1}{2}} \qquad (6)$$

The Equation (4) can be written as follow:

$$\Phi_w = \frac{2\pi^2}{\Phi_L^{\ 2}} - \frac{8\pi^4}{\Phi_L^{\ 4}} \qquad (7)$$

The functional relationship between Φ_w and Φ_L is:

$$\Phi_w \cdot \Phi_L^{\ 2} = b + \frac{a}{\Phi_L^{\ 2}} \qquad (8)$$

The constants a, b are determined using the experimental data from Palmer. The least square method was used to determine the constants a, b for three different areas which are shown in Equations (9), (10), and (11). The resulted curve is presented in Figure 1. The curve represents the imperfection profiles whose shape is an upheaval foundation. The portion of the curve with mild slop in Figure 1 corresponds to a single isolated imperfection in a horizontal profile. The final relationship represents to be bilinear, with

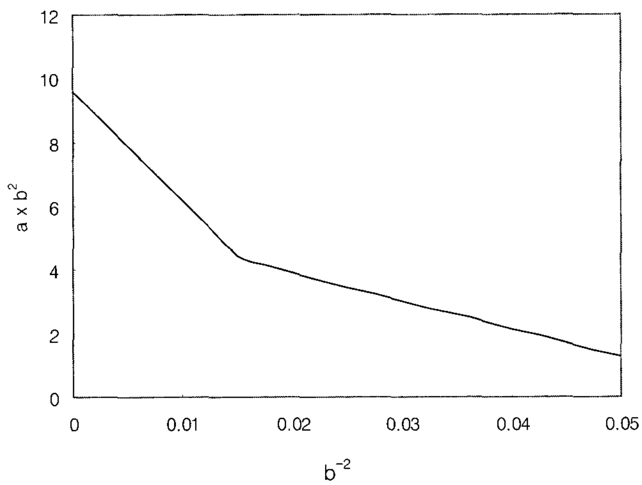

Fig. 1 Correlation of Experimental Results (Experiment by Palmer)

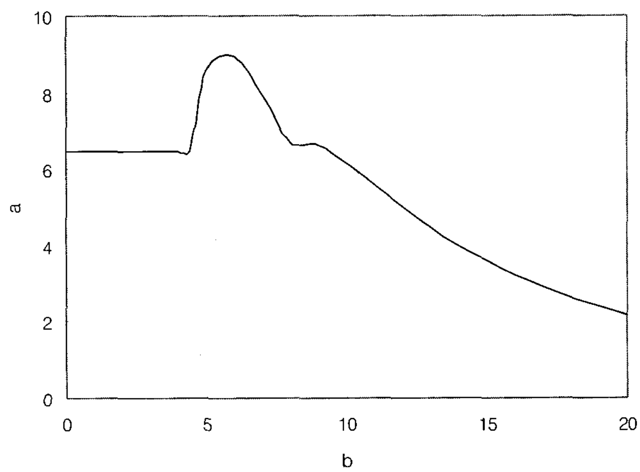

Fig. 2 Download Required & Length Parameter

one pair of values *a*, *b* corresponding to small values of Φ_L and a second pair to large values.

The third condition occurs a very short imperfection, so that the pipeline is only in contact with the crest of the imperfection. The download parameter is constant for the length parameter Φ_L less than 4.49, as shown Figure 2.
The results are combined in Figure 2, a universal curve that can be used directly for a preliminary design. The three conditions that give both the design download and the required parameters for stability are taken from Palmer.

$$\Phi_L < 4.49$$
$$\Phi_w = 0.0646 \tag{9}$$

$$4.49 < \Phi_L < 8.06$$
$$\Phi_w = \frac{5.68}{\Phi_L^2} - \frac{88.35}{\Phi_L^4} \tag{10}$$

$$\Phi_L > 8.06$$
$$\Phi_w = \frac{9.6}{\Phi_L^2} - \frac{304}{\Phi_L^4} \tag{11}$$

The imperfection length can be calculated from the formula given by Ellinas.

$$L = \left(\frac{72 \cdot EI \cdot d}{w_0}\right)^{\frac{1}{4}} \tag{12}$$

Where *EI* is the rigidity of pipe and w_0 is the submerged weight of the pipe. From Equations (6), (7), (9), (10), (11) and (12), a design formula for the download required for stability can be obtained as:

$$\Phi_L < 4.49$$
$$w = 0.0646 \cdot \frac{d \cdot P^2}{EI} \tag{13}$$
$$4.49 < \Phi_L < 8.06$$

$$w = 0.669 \cdot P \cdot \left(\frac{d \cdot w_0}{EI}\right)^{\frac{1}{2}} - 0.23 w_0 \tag{14}$$

$$\Phi_L > 8.06$$

$$w = 1.13 P \cdot \left(\frac{d \cdot w_0}{EI}\right)^{\frac{1}{2}} - 4.76 w_0 \tag{15}$$

These equations are used to derive the download required for a preliminary design.

The equation of the effective compressive force was taken from Ellinas.[2)]

$$P = E \cdot A \cdot \alpha \cdot \Delta T + \left(\frac{\pi}{4}\right) D_i^2 (1 - 2 \cdot \nu) \cdot \Delta P \tag{16}$$

where A is the cross section area of steel pipe, E is elastic modulus of steel, α is coefficient of thermal expansion, ΔT is temperature increment, ν is Poisson's ratio, ΔP is pressure differential between internal operating pressure and external hydrostatic pressure, and D_i is an inside diameter of the steel pipe.

3. Uplift Resistance of Cohesionless Soil

Buried pipelines can be covered by cohesionless materials such as sand, gravel, rock, etc. Then the uplift resistance can be described by the dead weight and the friction force component:

$$Q = W + S \tag{17}$$

The weight, ignoring the 'corners' at the pipeline sides, can be approximated as:

$$W = \gamma \cdot H \cdot D \tag{18}$$

where D is an outer diameter of the buried pipeline and H is the cover height of soil, γ is submerged unit weight of soil.
The shear forces assuming proportionality with the vertical effective stress and a friction coefficient $\tan\Phi$, can be written as:

$$S = H^2 \cdot \gamma \cdot K \cdot \tan\Phi \tag{19}$$

The coefficient of lateral earth pressure K is defined as the ratio of horizontal and vertical effective stresses. Equation (17) may then be rewritten as:

$$Q = \gamma \cdot H \cdot D + H^2 \cdot \gamma \cdot K \cdot \tan\Phi \tag{20}$$

The Equation (20) can be expressed with the load factor f_d as:

$$Q = \gamma \cdot H \cdot D + H^2 \cdot \gamma \cdot f_d \tag{21}$$

where the load factor is defined by multiplication of the coefficient of lateral earth pressure K and a friction coefficient of soil $\tan\Phi$.

For the most of cover conditions, the load factor varies between 0.3 and 0.5. Through the experimental data for gravel and rock dumps, the common load factor has a value of around 0.6 but it depends on the soil conditions. The total uplift resistance was calculated as follows:

$$R = Q + w_i \tag{22}$$

where R is the total uplift resistance and w_0 is the submerged weight of pipelines including the fluid content. The safety factor is defined as the ratio of the total uplift resistance and the download required for the stability of the pipeline.

$$S.F. = \frac{R}{w} \tag{23}$$

4. Effects of Temperature and Pressure

The example shows the effective axial force and safety factor due to pressure difference at operating temperature. Calculations were performed for a 16.828 cm (6.625-inch) outside diameter steel pipe with a 0.711 cm (0.28-inch) wall thickness. Figure 3 presents the effect of the pressure variations from 1380 pound per square inches (psi) to 2280 psi for a constant value of temperature difference 120°F. The effective axial force changes linearly by the pressure variation but the safety factors against upheaval buckling remains almost constant value of 3. Figure 4 presents the effective axial force and safety factors due to temperature difference between 20°F and 180°F for a constant pressure difference 1480 psi. The results on the effective axial force and safety factors are changing rapidly by temperature variations. Thus, pipelines with a high temperature have a tendency of low safety factors over the high pressure pipelines. Therefore, the effect of temperature is significant on the design of pipelines. Figures 5 and 6 show the effective axial forces and safety factors due to the various pressure and various temperature. These two figures present the results of the calculations based on the variation of the both temperature and pressure. The results confirm the effect of temperature is significant on the upheaval buckling.

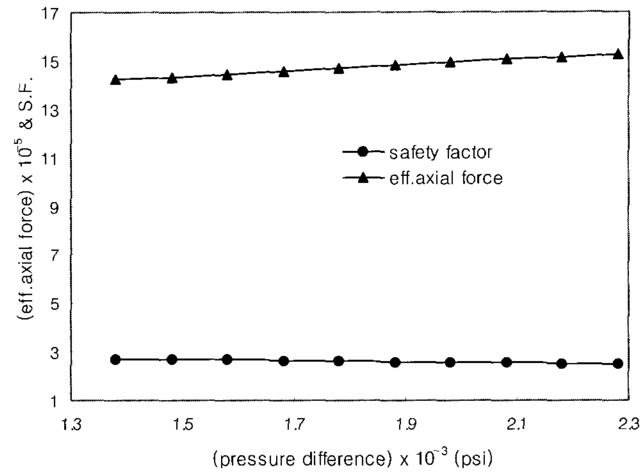

Fig. 3 Effect of Pressure at Temp. Difference 120°F.

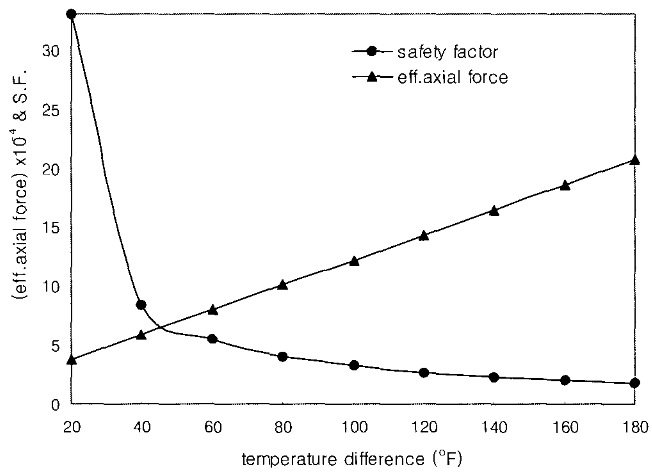

Fig. 4 Effect of Temperature at Press. Difference 1480 psi

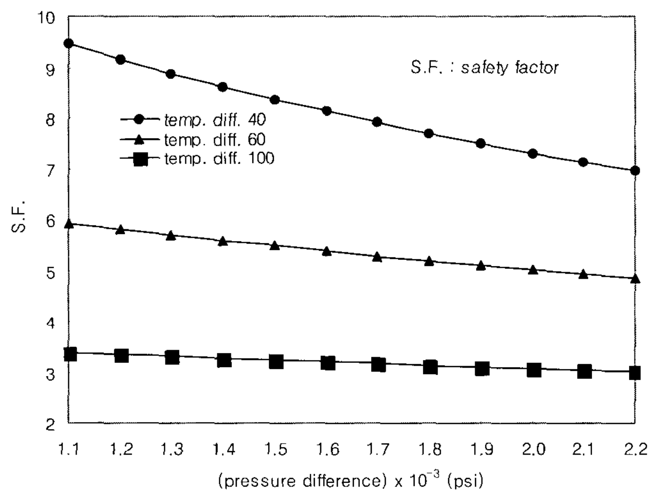

Fig. 5a Effect of Pressure at Various Temp. Difference

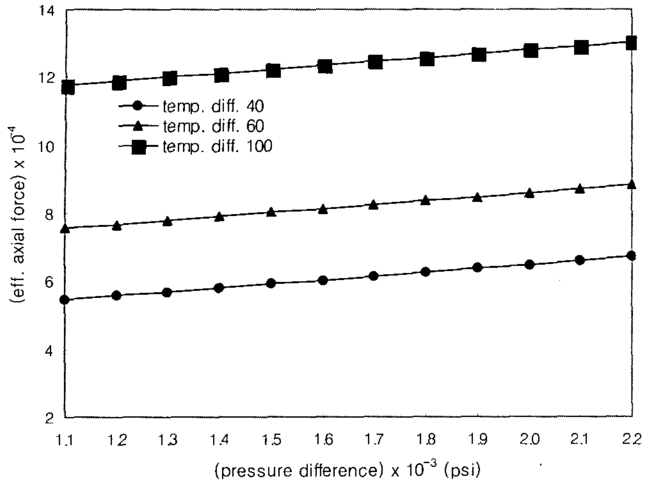

Fig. 5b Effect of Pressure at Various Temp. Difference

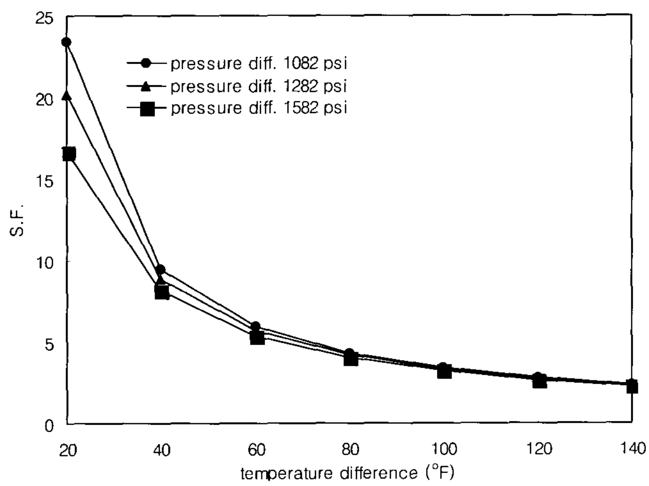

Fig. 6a Effect of Temperature at Various Press. Difference

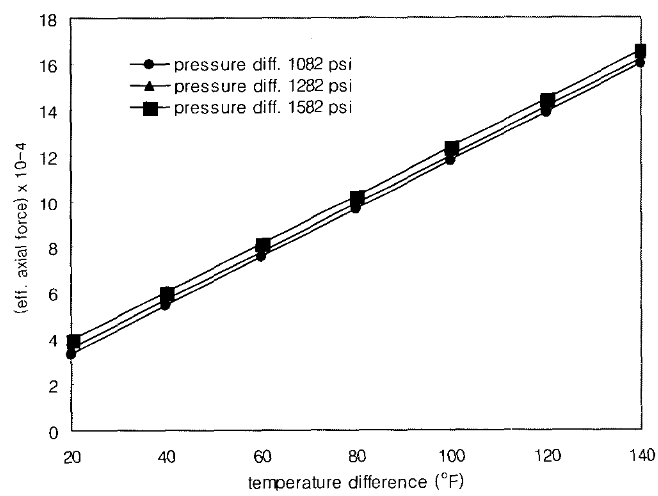

Fig. 6b Effect of Temperature at Various Press. Difference

5. Effect of Initial Imperfection

During the installation of a pipeline, the pipeline can be laid across an uneven seabed and buried later. The trenching and burial operations modify the profile of the foundation on which the pipeline is resting. Therefore, the original profile of the pipeline can be changed. If an obstruction on the seabed falls under the pipe, the profile of the pipeline may be bended upward. Figure 7 presents the safety factors by variation of the initial imperfections. The safety factors are changing very rapidly with respect to the value of initial imperfections. Therefore, the effect of initial imperfection is significant on the pipeline design.

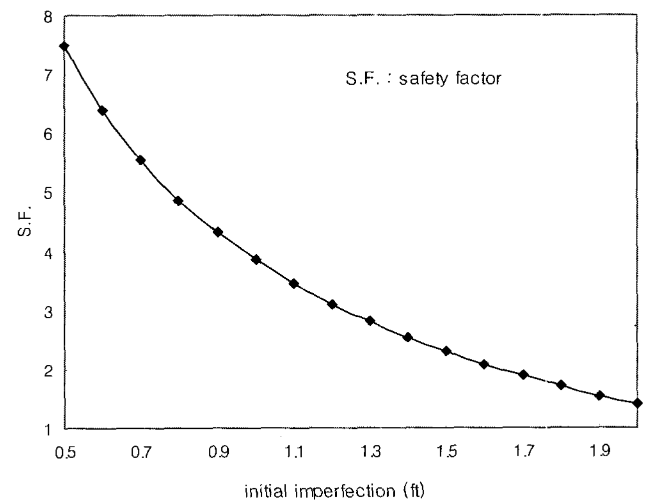

Fig. 7 Safety Factor due to Initial Imperfections

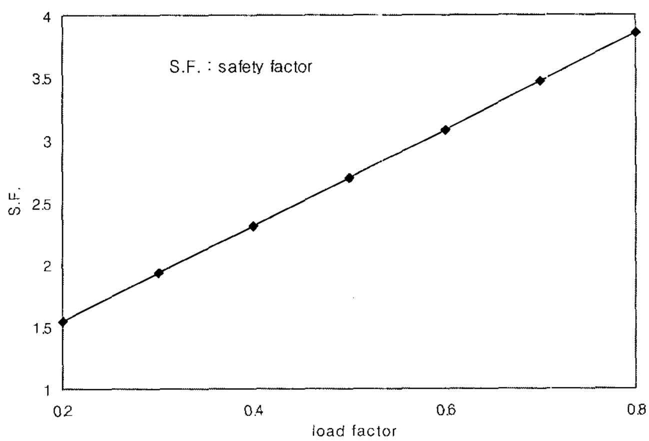

Fig. 8 Safety Factor due to Load Factors

6. Effect of Load Factor

The uplift resistance of the soil on the pipeline is a function of the dead weight of the soil and the amount of friction or shear force. The shear force depends on the cover height of soil and load factor. For the most cover conditions, the load factor varies between 0.3 and 0.5. Through the experimental data for gravel and rock dumps, the common load factor has a value of around 0.6 but it depends on the soil conditions. Figure 8 shows the safety factor changes linearly by changing load factor variations. The estimation of the load factor includes some uncertainties.

Therefore, the selection of the load factor is very important in the upheaval buckling analysis.

7. Concluding Remarks

A simple procedure for the analysis of the upheaval buckling was established by using a simplified method. The simplified method can be used for a preliminary design of the pipelines.

The results of calculations of effective axial forces and safety factors of the buried liquid pipeline due to the temperature, pressure, load factor and initial imperfection are as follow:

1) The effect of temperature is greater than the effect of pressure on effective axial force and upheaval buckling of the pipelines.
2) The initial imperfection is very sensitive to the upheaval buckling.
3) The load factor is also very sensitive to upheaval buckling. Therefore, the conservative values of the load factors are recommended for a preliminary design.

Acknowledgment

This study has been undertaken as a part of the project financially supported by the BK 2001.

References

Bai, Y. (2001), "Pipelines and Risers", Prepared for M.Sc. Course TE 6075, Elsevier.

Ellinas, C. P., and Supple, W. J. (1990). "Prevention of Upheaval Buckling of Hot Submarine Pipelines by Means of Intermittent Rock Dumping", Offshore Technology Conference 6332, pp 519-528.

Guijt, J. (1990) "Upheaval Buckling of offshore pipelines, Overview and Introduction", Offshore Technology Conference 6487, pp 573-582.

Guijt, J. (1990). "Upheaval Buckling of offshore pipelines, Overview and Introduction", Offshore Technology Conference 6487, pp 573~582.

Palmer, A. C., and Andrew Palmer & Assocs. (1990). "Design of Submarine Pipelines Against Upheaval Buckling", OTC 6335, pp 551-560.

Schaminee, P. E. L., Zorn, N. F., and Schotman, G. J. M. (1990). "Soil Response for Pipeline Upheaval Buckling Analyses: Full-Scale Laboratory Tests and Modeling", Offshore Technology Conference 6486, pp 563-572.

2001년 6월 16일 원고 접수
2002년 1월 18일 최종 수정본 채택