DMT dissipation analysis using an equivalent radius and optimization technique

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ABSTRACT: The worldwide spread of the DMT lies on its simplicity, cost effectiveness, rapid and repetitive use for geotechnical engineering practice. Despite of the simple equipment and operation, various soil parameters – e.g., K_o, OCR, s_u, ϕ, c_h, k_h, γ, M, u_o – can be obtained and have been successfully applied to geotechnical design practice. However, most of those parameters were obtained from the calibrated relationship between the real soil parameter and indices from DMT test. Among them, the estimation of horizontal coefficient of consolidation is more complex due to the inherent difficulty on analyzing a plane strain deformation of the soil around DMT blade during its penetration. Therefore, empirical and semi-empirical methods that use the theoretical solution developed for piezocone with some assumptions have been used to estimate the coefficient of consolidation from dilatometer dissipation test.

In this paper, a new method is proposed which uses an optimization technique and an equivalent radius that is same area with the DMT blade to estimate the coefficient of consolidation from the dilatometer p_2-value dissipation test. Using the BFGS optimization technique, the horizontal coefficient of consolidation that minimizes the differences between the predicted excess pore pressures and measured excess pore pressures (p_2) is determined. Validity of the proposed method was confirmed by comparing the obtained horizontal coefficients of consolidation with those of other interpretation methods and oedometer for the Yang-san site. It has been known that proposed method can give more precise horizontal coefficient of consolidation than other methods do. In addition, the possible determination of representative coefficient of consolidation corresponding to entire dissipation process was also shown from the good agreements between measured and predicted excess pore pressures over whole dissipation stage.

1 INTRODUCTION

In-situ dissipation tests are increasingly conducted in recent years to evaluate a horizontal coefficient of consolidation (c_h) of soft clay layer. Nevertheless, the dissipation tests by flat Dilatometer have not been carried out so frequently. Some researchers have proposed empirical analysis procedures to interpret the dissipation curve obtained from the flat DMT test. Even though it does not have a porous element for measuring the dissipation characteristics of excess pore water pressure induced by the penetration of Dilatometer blade, it has some advantages over piezocone test. The most favorable aspect of flat DMT dissipation test is believed to be the absence of problems concerning the filter element such as smearing, loss of saturation, clogging, etc. Besides, the horizontal coefficient of consolidation obtained by flat DMT is the representative of an average value of steel membrane contact areas (radius = 60mm), while the piezocone measures the dissipation of pore pressure through the very narrow 5mm band element.

However, DMT methods empirically use theoretical solutions developed for the piezocone dissipation analysis. The present three methods are two DMTC methods [p_2-log t method proposed by Robertson et al. (1988) and C-$\sqrt{t}$ method suggested by Schmertmann (1988)] and one DMTA method developed by Marchetti & Totani (1989). The in-situ determination of horizontal coefficient of consolidation by Piezocone dissipation test has been studied from the early 1970s'. A number of researchers have proposed several available theoretical time factors since then. Presently, it has been well known that the c_h obtained from CPTU dissipation test represents relatively well the in-situ consolidation characteristics, better than those determined by laboratory tests. Among those theoretical solutions for the CPTU dissipation analysis, Torstensson's solution (1977) and Gupta's solution (1983) have been used to interpret the dissipation characteristics of flat DMT in p_2-log t method and C-$\sqrt{t}$ method, respectively.

Totani et al. (1998) compared the coefficient of consolidation results obtained by DMTC (especially p_2-log t method) and DMTA dissipation tests with laboratory results. They pointed out that it is not possible to comparatively evaluate the quality of two methods. Therefore, the validity of those methods has to be verified before using under specific local site characteristics.

In this study, a new interpretation method for DMT dissipation test is proposed using an equivalent radius and optimization technique. Validity of the proposed method was confirmed by interpreting the flat DMT dissipation tests carried in Yangsan site of Korea and comparing the estimated coefficients of consolidation with reference values. For the purpose of comparison, undisturbed samples were taken and oedometer tests were carried out.

2 INTERPRETATION METHODS FOR DMT DISSIPATION TEST RESULTS

2.1 *DMTC method*

In this method, there are two types of interpretation. One is the p_2-log t method developed by Robertson et al. (1988) and the other is the C-$\sqrt{t}$ method suggested by Schmertmann (1988). This method consists of stopping the blade at a given depth and taking a sequence of readings A-B-C at different times. The p_2-log t method uses a dissipation curve of p_2, which is an adjusted C-reading for the membrane stiffness, while the C-$\sqrt{t}$ method uses the uncorrected C-reading. The p_2-log t method was developed upon the basic fact that the value of p_2 is essentially the penetration pore pressure of DMT blade and the final p_2 value in a complete dissipation represents the static pore pressure u_o. This fact has been verified by several researchers for NC and slightly OC clays. Other difference between those two methods is determination of the elapsed time t_{50} for estimating the c_h. The p_2-log t method uses logarithmic time scale plot, while the C-$\sqrt{t}$ method uses $\sqrt{time}$ scale plot.

The equation that is used for evaluating the c_h in both methods is as follows:

$$c_h = \frac{R^2 \cdot T_{50}}{t_{50}} \quad (1)$$

where R = equivalent radius, T_{50} = theoretical time factor for 50% degree of dissipation, t_{50} = elapsed time for 50% degree of dissipation.

2.2 *Equivalent radius and theoretical time factor T*

To use equation (1), Robertson et al. (1988) and Schmertmann (1988) had proposed different equivalent radius and used different theoretical time factor as shown in table 1.

Table 1. Summary of equivalent radius and time factor of DMTC method

	p_2-log t method	C-$\sqrt{t}$ method	Remark
Equivalent Radius	20.57mm considering the section area of DMT blade	24.5mm R^2=600mm^2	DMT blade dimension (95mm ×14mm)
Theoretical time factor T_{50}	Torstensson (1977) Cylindrical Cavity Expansion solution	Gupta (1983) Successive Spherical Cavity Expansion solution	C-$\sqrt{t}$ method can consider the location of pore pressure measurement

2.2.1 *Equivalent radius*

The p_2-log t method uses the equivalent radius of R=20.57mm which has the same section area as DMT blade, while C-$\sqrt{t}$ method proposed R^2=600mm^2, which results in the enlarged equivalent radius R=24.5mm. However, comparison between maximum volumetric and shear strains developed by insertion of DMT blade and cone shows that the maximum volumetric strain of cone is 3 times larger than that of DMT (Schmertmann, 1988). This kind phenomenon has been also found theoretically by Baligh & Scott (1975).

2.2.2 *Theoretical solution*

As summarized above in Table 1, p_2-log t method uses Torstensson's (1977) cylindrical cavity expansion solution and C-$\sqrt{t}$ method uses Gupta's (1983) successive spherical cavity expansion solution. Major difference between those two theoretical solutions is whether it can consider the measuring point of pore pressure which is developed by penetration of dilatometer or not. Schmertmann (1988) used the Gupta's theoretical solution, which was obtained 4 times behind of equivalent radius from the tip, to consider the location of measuring pore pressures.

Figure 1 shows the comparisons between penetration pore pressures measured from the three different locations of piezocone - u_1, u_2, and u_3 – and measured from the porous stone located at center of steel membrane of DMT blade (Robertson et al., 1988). From the figure, it was found that the penetration pore pressures measured from the DMT blade are similar to those measured at the u_3 location (behind the sleeve fiction) than the location u_2. It was also known that initial excess pore pressure magnitude decreases from the tip to the sleeve friction but the dissipation time becomes longer (Baligh & Levadoux, 1980). From these facts, it is more appropriate to use theoretical solution that can consider the pore pressure measurement point of DMT blade.

BACK

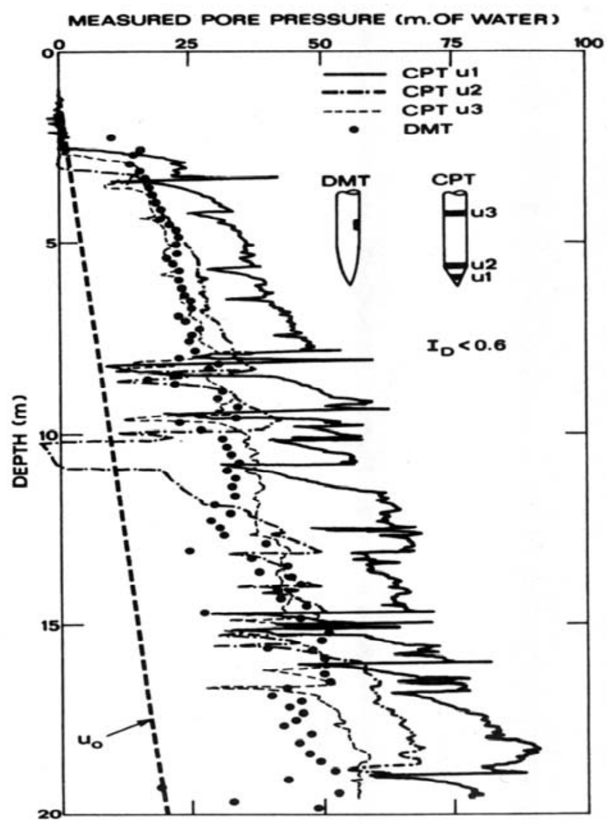

Figure 1. Comparison of penetration pore pressure measured by DMT and Piezocone (Robertson et al., 1988)

3 DETERMINATION OF HORIZONTAL COEFFICIENT OF CONSOLIDATION USING OPTIMIZATION TECHNIQUE

In this research, a direct optimization technique that determines unknown soil parameters by minimizing the objective function defined as the sum of squares of differences between calculated and measured quantities [Eqn (2)] is adopted. It is implemented in the program which can simulate the penetration process of the DMT simulated with equivalent radius and the linear-uncoupled consolidation process. By introducing an optimization technique to dissipation analysis, horizontal coefficient of consolidation, which reflects the dissipation trend, can be obtained (Kim & Lee, 2000).

$$f(\mathbf{x}) = \sum_{n=1}^{ntime} (u^n - U^n)^2 \qquad (2)$$

where ntime = number of measuring time steps; u^n = calculated pore pressure at time n; U^n = measured pore pressure at time n, and $\mathbf{x}$ = vector of design variables.

Based on research results (Robertson et al., 1988; Lutenegger, 1988; Schmertmann, 1988), it is assumed that dissipation process around the DMT blade is predominantly horizontal, therefore, horizontal coefficient of consolidation has been considered as design variable [Eqn (3)].

$$\mathbf{x} = (c_h) \qquad (3a)$$

$$\mathbf{x}_{lower} \le \mathbf{x} \le \mathbf{x}_{upper} \qquad (3b)$$

In Eqn (3), $\mathbf{X}_{lower}$ and $\mathbf{X}_{upper}$ are lower and upper bound values for the variables, respectively. The values of $\mathbf{X}$, $\mathbf{X}_{lower}$, and $\mathbf{X}_{upper}$ can be reasonably estimated by either laboratory tests, in-situ tests, or engineering judgments.

To consider the measuring point of pore pressure, excess pore pressures calculated 4 times behind of equivalent radius from the tip were used as the calculated pore pressures u^n shown in equation (2). Equivalent radius was selected as 20.57mm, which has the same section area with DMT blade. To solve the formulated unconstrained optimization problem, the BFGS (Broyden-Fletcher-Goldfarb-Shanno) technique (Arora, 1989), which is the most popular and has been proven to be the most effective in application to unconstrained optimization problems, was used. The gradient vector of the objective function was calculated by the finite difference scheme because of the highly implicit nature of the objective function.

4 APPLICATION OF THE PROPOSED METHOD

4.1 *Comparison of the horizontal coefficient of consolidation*

To validate the proposed method, 6 DMT dissipation test results, which were carried at the Yangsan siteof Korea, were analyzed. Coefficients of consolidation determined from the proposed method are compared with those calculated from other DMTC interpretation methods and laboratory test results. Basic soil properties, rigidity indices, and soil classification results for the sample obtained from the test site are summarized in Table 2.

Table 2. Basic soil properties of Yangsan site (Lee et al., 2001)

Borehole	Depth (m)	Undrained shear strength s_u (kPa)	E/s_u	Liquid limit	Plastic index	USCS
YS -1	15	60.8	110	56.3	28.9	CH
YS -1	18	68.6	85	47.3	24.9	CL
YS -2	12	52.0	110	54.1	30.8	CH
YS -2	15	60.8	90	55.4	30.1	CH
YS -3	19	86.3	85	47.3	24.0	CL
YS -3	24	127.5	70	43.3	19.2	CL

BACK

Figure 2 shows the dissipation test results that were carried by Lee et al. (2001). The early phase up to around 50% degree of dissipation is used as an input degree of dissipation data. An arrow on each dissipation curve points 50% degree of dissipation which is a half of initial excess pore pressure.

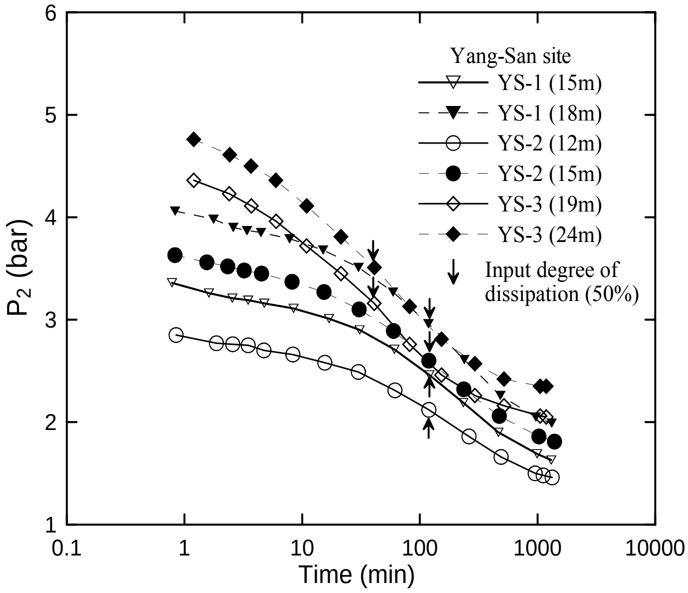

Figure 2. DMT p_2 dissipation curves measured at Yangsan site (Lee et al., 2001)

Coefficients of consolidation are compared in Table 3 and Figure 3. In Figure 3, x–axis shows the coefficient of consolidation estimated from p_2-log t method. As a reference value, coefficient of consolidation obtained from oedometer test for the undisturbed sample was used. It has been known that the horizontal coefficient of consolidation is generally larger than vertical coefficient of consolidation. Lacerda et al. (1977) proposed a correlation between vertical and horizontal permeability considering the void ratio based on the laboratory permeability test results. Although little experimental information exists on the ratio of horizontal to vertical compressibility, this ratio has been believed to be close to unity for OCR $\approx$ 1 and, in practice, the compressibility of clays is generally considered isotropic (Parry & Wroth, 1977). Therefore, the ratio of c_h/c_v can be obtained from the ratio k_h/k_v proposed by Lacerda et al. (1977) based on the void ratio of Yangsan site. In this study, horizontal coefficient of consolidation were obtained from the following equation (4) using the ratio of k_h/k_v as 2.2.

$$c_h = \left(\frac{k_h}{k_v}\right) \cdot c_v = 2.2 \cdot c_v \tag{4}$$

where c_h = horizontal coefficient of consolidation, c_v = vertical coefficient of consolidation, k_h = horizontal coefficient of permeability, k_v = vertical coefficient of permeability

As shown in the Figure 3, horizontal coefficients of consolidation determined from the proposed method were obtained consistently with r^2=0.99 and magnitude of those values are similar with those determined from the oedometer except one point, which is indicated by dot circle and might be affected by sample disturbance.

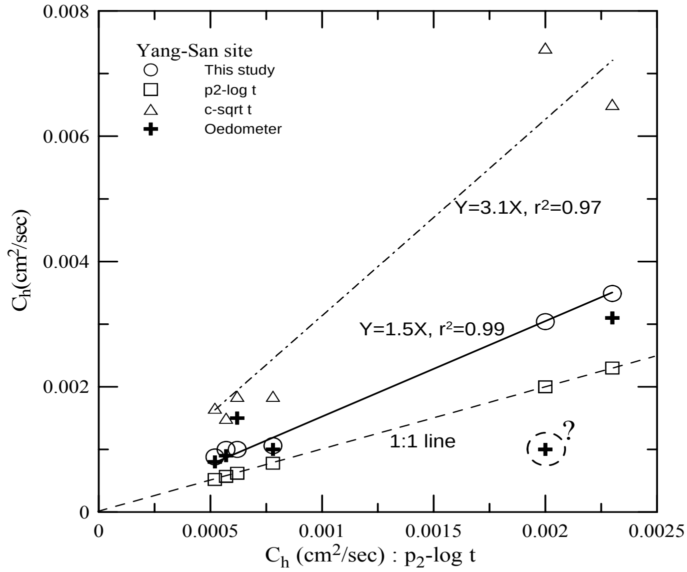

Figure 3. Comparisons of coefficients of consolidation

Table 3. Comparisons of the coefficient of consolidation

Location	This study	P_2-log t method	C-$\sqrt{t}$ method	Oedometer*
	($c_h \times 10^{-3}\,cm^2/sec$)			
YS-1(15m)	1.0	0.6	1.9	1.5
YS-1(18m)	1.1	0.8	1.9	1.0
YS-2(12m)	0.9	0.5	1.7	0.8
YS-2(15m)	1.0	0.6	1.5	0.9
YS-3(19m)	3.0	2.0	7.4	1.0
YS-3(24m)	3.5	2.3	6.5	3.1

* calculated using Eq. (4)

Coefficients of consolidation determined from the proposed method fall between those determined by p_2-log t method and C-$\sqrt{t}$ method. Comparing coefficients of consolidation determined from the laboratory with those determined from p_2-log t and C-$\sqrt{t}$ method, p_2-log t method underestimates while C-$\sqrt{t}$ method over-estimates. It supports that equivalent radius and theoretical solution integrated with optimization technique is effective to model the penetration and dissipation procedure of dilatometer test.

4.2 *Prediction of dissipation behavior over the entire dissipation range*

Present interpretation methods – i.e., p_2-log t method and C-$\sqrt{t}$ method – determine the coefficient of consolidation from the particular degree of dissipa-

BACK

tion (or particular elapsed time t_{50}) using equation (1). Therefore, back calculated dissipation curve using those coefficients of consolidation would match exactly at one point t_{50}. However, the proposed method uses dissipation trend by introducing the optimization technique. Figure 4 shows the effectiveness of optimization technique and dissipation trend by comparing between measured and predicted dissipation curve over the entire dissipation range. Predicted dissipation curve is calculated by simulating the penetration of DMT blade and dissipation behavior of excess pore pressure around DMT blade with coefficient of consolidation determined from the proposed method. Predicted dissipation curves coincide well with measured dissipation curves. From the result shown in the Figure 4, it can be concluded that the proposed method can evaluate the representative coefficient of consolidation over the various stress levels which were experienced during entire dissipation range.

5 CONCLUSIONS

A new method, which uses an equivalent radius (R=20.57mm) and integrates the theoretical solution that can consider the measuring point of penetration pore pressure and optimization algorithm, was proposed to estimate the coefficient of consolidation from the DMT p_2 dissipation data. The proposed method estimates with higher precision than other interpretation methods (such as p_2-log t or C-$\sqrt{t}$ methods) the coefficients of consolidation determined in-situ, particularly when compared with laboratory test results. Dissipation curve calculated with coefficient of consolidation determined from the proposed method coincide well with measured dissipation curve over the entire dissipation range. It can be concluded that the optimization technique can evaluate with good representativeness the coefficient of consolidation over the various stress levels experienced during entire dissipation range, by reflecting the early phase of dissipation trend.

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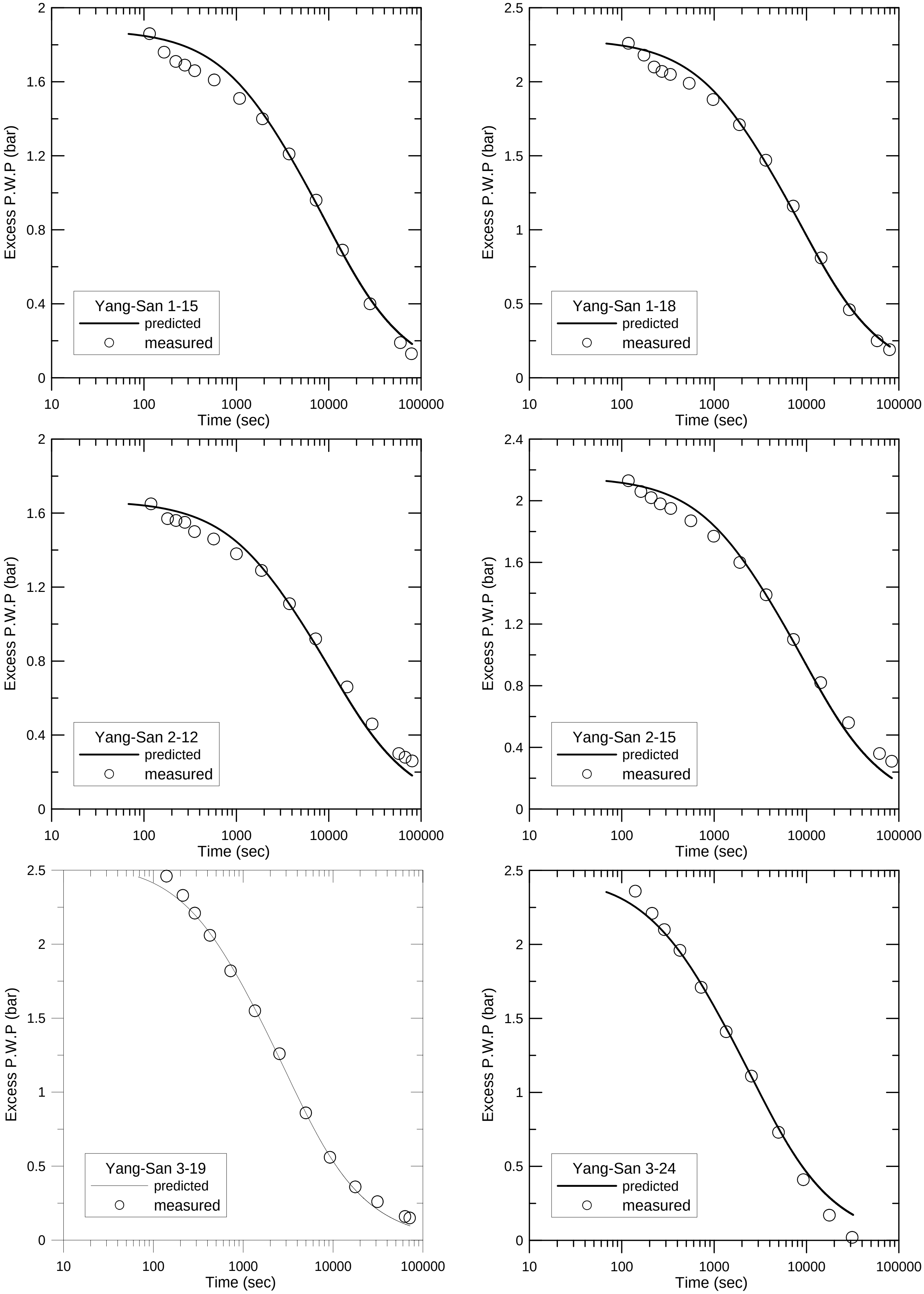

Figure 4. Comparisons of the entire dissipation behavior between calculated and measured dissipation curve

BACK