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Post-Construction Settlement Calculation and Prediction for Group Piles Foundation of High Speed Railway Bridge

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Abstract
On the basis of and after adjustment to Consolidation Settlement Theory, a calculation method for post-construction settlement for high speed railway group piles foundation is put forward and the calculation formula is deduced accordingly. By the application of Gray System Theory GM (1,1) model, metabolism GM (1,1) model is worked out. Through comparative analysis with settlement observation data of one pier of Yunzaobang major bridge, the post-construction calculation method and Gray System Theory prediction method proposed in this paper are proven applicable in engineering practice.
Key words: High speed railway; Group piles foundation; Post-construction settlement; Calculation; Gray model; Settlement prediction

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INTRODUCTION
As far as high speed railway or passenger dedicated railway is concerned, over uneven post-construction settlement of bridge and culvert foundation will cause track unsmoothness, and further incur train vibration, increase of dynamic action between wheel and rail, significant dropping of stability, comfort and safety indexes during high speed operation, and may even result in derailment.

The deformation character of group piles foundation settlement is the synthesis result of interaction among the pile, pile cap and foundation soil. Due to polytropy of foundation soil, variousness of pile construction technique, pile shape and pile arrangement, group piles foundation settlement calculation poses a difficult problem for the design work of pile foundation, and post-construction settlement calculation for group piles foundation is even more difficult.

Currently, the overall settlement of the pile foundation is the concern of both domestic and overseas researchers, while less attention is paid to post-construction settlement. In this case, a suitable method of final settlement and post-construction settlement calculation for bridge foundation in soft soil section is in need. The calculation method should be worked out on the basis of existing practicable theory, by means of which, the regularity of changes of group piles foundation settlement with time lapse will be sought out, a post-construction relationship curve will be established through prediction, major factors that influence group piles foundation settlement will be analyzed, and construction measures to reduce post-construction settlement will be proposed.

In this paper, on the basis of settlement observation data from Shanghai-Nanjing section of Beijing-Shanghai high speed railway, computational analysis is carried out concerning settlement change process of group piles foundation with time lapse. Gray System Theory model established thereby is applied to simulate settlement prediction, and the result is analyzed and compared with observation data.

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1. GROUP PILES FOUNDATION POST-CONSTRUCTION SETTLEMENT CALCULATION

In Interim Design Provisions for Beijing-Shanghai High Speed Railway, post-construction settlement is defined as: the difference between final settlement of the infrastructure and settlement of the infrastructure at the moment of track laying. According to this definition, post-construction settlement of bridge foundation is the consolidation settlement of the soil compressive stratum (bearing stratum) under foundation sub-surface after track laying work starts. Since the weight of track is relatively small, the constant load of railway is all on the foundation at the moment of track laying. The train axle load is small and the operation speed is high. Before consolidation settlement from dynamic load occurs, the train has passed. The dynamic loading test carried out at Kunshan experimental section of Beijing-Shanghai line has proved that the train will not cause cumulative settlement deformation to the piles. Therefore, post-construction settlement of pile foundation could be calculated from the consolidation settlement of the foundation under constant load as track laying work commences. Post-construction settlement Sgh is represented as:

$$S_{gh}=S - S_e - S_t \,. \tag{1}$$

In this formula, S_{gh} stands for post-construction settlement, S for final settlement (cumulative settlement), S_e for immediate settlement, and S_t for consolidation settlement at the moment of track laying.

If a uniformly distributed pressure p is suddenly applied to the top surface of the compressive stratum, then the pressure at any point within the compressive stratum is p, and the distribution of loading stress (attached stress) is in rectangular shape. Under this condition, Terzaghi one dimensional consolidation degree calculation formula (Zhe, 1998) is:

$$U = \frac{S_t}{S} = 1 - 2\sum_{m=0}^{\infty} \frac{1}{M^2} e^{-M^2 T_v} \,. \tag{2}$$

In this formula, U stands for consolidation degree, represents the percentage of settlement completed at compressive stratum under load after a certain time t; S for final settlement (cumulative settlement) of compressive stratum, could be calculated by layer wise summation method or other method stated in relevant specifications;

S_t for settlement after time t;

$M=\pi(2m+1)/2$, m is positive integer like 0, 1, 2, … ;

$T_v=c_t\, I\, H^2$ (T_v is called time factor);

C_v for consolidation coefficient (cm^2/s or m^2/s);

H is the whole thickness of the compressive stratum in the case of single-side permeable, or is half of the compressive stratum thickness in the case of both-side permeable.

The above consolidation degree formula is deduced on the basis that the attached stress distribution is rectangular, and that the loading stress is applied to the compressive stratum once and for all. Therefore, Formula (2) could not be directly applied to the calculation of bridge foundation consolidation degree for the following reasons: a) The distribution of attached stress under bridge foundation is not in rectangular shape but trapezoid shape; b) The loading stress for bridge foundation is not applied suddenly, but gradually within the construction period. When applied to practical bridge foundation settlement calculation, the above formula must be adjusted in the following way:

1.1 Calculation of Consolidation Degree as Stress Distribution Is in Trapezoid Ahape and Under Different Permeable Conditions

There are two situations for consolidation degree calculation as stress distribution is in trapezoid shape:

(a) Trapezoid shape stress distribution and double-side pervious compressive stratum In this case, Formula (2) could be directly applied to calculate U_1:

$$U_1 = U = 1 - 2\sum_{m=0}^{\infty} \frac{1}{M^2} e^{-M^2 T_v} \,. \tag{3}$$

Formula (3) has fast series convergence, so the initial four items are adequate to meet the needs:

$$U_1 = 1 - \frac{8}{\pi^2} e^{-\frac{\pi^2}{4}T_v} - \frac{8}{9\pi^2} e^{-\frac{9\pi^2}{4}T_v} - \frac{8}{25\pi^2} e^{-\frac{25\pi^2}{4}T_v} - \frac{8}{49\pi^2} e^{-\frac{49\pi^2}{4}T_v} \,. \tag{4}$$

Trapezoid shape stress distribution and single-side pervious compressive stratum

In this case, consolidation degree U_2 will be calculated by the application of the following formula:

$$\begin{aligned} U_2 &= U + \frac{r-1}{r+1}(U - U') = \frac{2r}{r+1}U - \frac{r-1}{r+1}U' \\ &= \frac{2r}{r+1}\Big(1 - \frac{8}{\pi^2} e^{-\frac{\pi^2}{4}T_v} - \frac{8}{9\pi^2} e^{-\frac{9\pi^2}{4}T_v} - \frac{8}{25\pi^2} e^{-\frac{25\pi^2}{4}T_v} \\ &\quad - \frac{8}{49\pi^2} e^{\frac{49\pi^2}{4}T_v} - \frac{r-1}{r+1}\Big(1 - \frac{32}{\pi^3} e^{-\frac{\pi^2}{4}T_v} - \frac{32}{27\pi^3} e^{\frac{9\pi^2}{4}T_v} \\ &\quad - \frac{32}{125\pi^3} e^{\frac{25\pi^2}{4}T_v} - \frac{32}{343\pi^3} e^{\frac{49\pi^2}{4}} T_v\Big) \,. \end{aligned} \tag{5}$$

In this formula, $U' = 1 - 4\sum_{m=0}^{\infty} \frac{(-1)^m}{M^3} e^{-M^2 T_v}$.

$r=\sigma_a/\sigma_b$, among which, σa and σb stands for the width of the upper side and the lower side of the trapezoid respectively, and the other symbols stand for the same as before.

1.2 Calculation of Consolidation Settlement as Stress Is Applied Gradually

In actual construction practice, bridge construction period is quite long, S_t-t curve (S_t-U_1 or S_t-U_2 curve converted from Formula (2)), determined by Formula (4) and (5), could not represent the actual settlement process, and requires empirical modification by the application of similar method to Terzaghi formula according to increase of loading stress.

As shown in Figure 1, supposing the loading stress at the foundation sub-surface increases during the construction period along the time line, stops increase after completion and becomes constant, and by setting bridge construction period as T_0, modification could be carried out under the following three situations according to different relationship between different time t and T_0:

(a) When $t=t_1<T_0$

Let the corresponding loading stress for t_1 be p_1 (the loading stress increases from 0 to p_1, $p_1<p$), and let settlement S_{t1} after t_1 be equal to the settlement of sudden loading stress p_1 after $t_1/2$. Settlement S' of sudden loading stress p after $t_1/2$ could be directly located from the S_t-t dashed curve. S' could be calculated from the following formula:

$$S' = U(\frac{t_1}{2}) \cdot S \; . \qquad (6)$$

In this formula, $U(t1/2)$ stands for the consolidation degree calculated out by substitution of sudden loading stress p and time $t_1/2$ in Formula (4) or (5);

S for final settlement.

S_{t1}, settlement of sudden loading stress after $t_1/2$, could be calculated from $S_{t1}=SP_1/P=S'_{t1}/T_0$. After substitution of Formula (6) in it:

$$S_{t1} = S' \frac{t_1}{T_0} = U(\frac{t_1}{2}) \cdot \frac{t_1}{T_0} \cdot S \; . \qquad (7)$$

S_{t1} in the above formula is the settlement of gradually increasing loading stress p_1 after t_1, as shown in Figure 1 S_t-t solid curve.

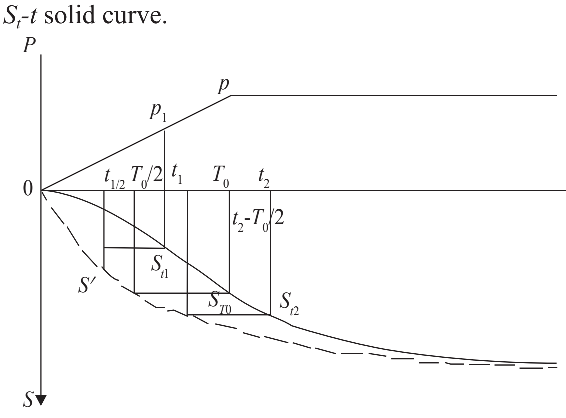

Figure 1
Modified Consolidation Settlement Under Gradually Increasing Loading Stress

(b) When $t=T_0$

The corresponding loading stress for t is p, and the settlement S_{T0} after t_1 equals to the settlement of sudden loading stress p after $T_0/2$, which could be directly located from the S_t-t dashed curve where $t=T_0/2$, as shown in the S_t-t solid curve in Figure 1.

$$S_{T0} = U(\frac{T_0}{2}) \cdot S \; . \qquad (8)$$

(c) When $t=t_2>T_0$

The corresponding loading stress is always p, but the corresponding settlement S_{t2} should equal to the settlement of sudden loading stress after t_2-$T_0/2$. In Figure 1, the value could be located from the S_t-t dashed curve where $t=t_2$-$T_0/2$, and then shifted to the position $t=t_2$. As t_2 increases, the modified curve (dashed curve) will come closer and closer to the theoretical curve, as shown in Figure 1 the S_t-t solid curve .

$$S_{t2} = U(t_2 - \frac{T_0}{2}) \cdot S \; . \qquad (9)$$

1.3 Calculation of Post-Construction Settlement

According to the permeable feature of the bearing stratum under the pile sub-surface and the above calculation formula for consolidation degree and consolidation settlement, calculation of post-construction settlement could be determined under the following three situations:

(a) Situation A

If the bearing stratum (compressive stratum) under the pile sub-surface consists of sandy soil or pebble soil, which has very good permeability, settlement caused by gradually increasing loading stress will complete in very short time, and settlement after construction period is very small. In this case, post-construction settlement S_{gh} is approximately 0:

$$S_{gh}=0. \qquad (10)$$

(b) Situation B

If the compressive stratum has ordinary permeability and track laying will immediately start after completion of bridge deck work, Formula (8) will be applied for the calculation of consolidation settlement, and the formula for post-construction settlement S_{gh} is:

$$S_{gh} = S - S_{T0} = [1 - U(\frac{T_0}{2})] \cdot S \; . \qquad (11)$$

(c) Situation C

If the compressive stratum has ordinary or poor permeability ($\boldsymbol{C}_v$ or k is very small), and predicted post-construction settlement after construction period (T_0) is more than permissible value, after construction period, the structure will be allowed to stand for some time (t_2-T_0) before track-laying work starts. In this case, Formula (9) will be applied for the calculation of consolidation settlement, and the formula for post-construction settlement S_{gh} is:

$$S_{gh} = S - S_{t2} = [1 - U(t_2 - \frac{T_0}{2})] \cdot S \ . \quad (12)$$

2. GRAY SYSTEM THEORY BASED POST-CONSTRUCTION SETTLEMENT PREDICTION FOR GROUP PILES FOUNDATION

Observation data could be applied to predict the relationship between settlement and time through the application of different prediction methods, among which, double curve method, index curve method and Poisson curve method are more frequently used ones. For structural objects constructed on the foundation of plastic clay, part of the settlement procedure completes during construction period, and the remaining procedure will complete during standing and operation period. How to use the settlement observation data collected during early construction period to predict the settlement procedure at later construction period and post-construction period according to the time line is of great significance. Gray System Theory is widely applied in recent years and provides possible solution to this topic.

Gray Model, GM in short, is the basic model of Gray System Theory, and is also the basis of Gray Control Theory. The general Gray Model is GM (h, n) model, representing a n-order differential equation of h variables. Currently, GM (1,1) model, a single sequence first-order linear dynamic differential equation, is the most widely applied model in the prediction study of deformation problems in geotechnical engineering. The settlement deformation prediction method proposed in this paper is based on GM (1,1) model.

2.1 GM (1,1) Model for Bridge Group Piles Foundation Settlement Prediction

In the prediction process, the settlement of group piles foundation is represented as variable X in GM (1,1) (Liu, Guo, & Dang, 1999; Deng, 1987). The method of prediction is shown as following:

Set $\{X^{(0)}(t_i)\}$ as the original time sequence of a settlement with equal time interval

$$X^{(0)}=(X^{(0)}(t_1), X^{(0)}(t_2),\cdots, X^{(0)}(t_n)) \ , \quad (13)$$

t_1, t_2, …, t_n is the corresponding time point to the settlement sequence. Interval Δt_i= constant, so sequence number k (k = 1, 2, …, n) could be used to substitute time point t_k.

By one accumulated generating operation to the original time sequence of settlement, sequence $X^{(1)}$ will come out as:

$$X^{(1)}=(X^{(1)}(1), X^{(1)}(2), \cdots, X^{(1)}(n)) \ . \quad (14)$$

Whereas,

$$X^{(1)}(i) = \sum_{k=1}^{i} X^{(0)}(k), i = 1,2,\cdots,n \ .$$

The differential equation of GM(1, 1) model of $X^{(1)}$ will be established:

$$\frac{dX^{(1)}}{dt} + aX^{(1)} = u \ . \quad (15)$$

The parameter sequence is represented as **â**, and by the application of least square method, â will be solved as:

$$\hat{a} = \begin{bmatrix} a \\ u \end{bmatrix} = (B^T B)^{-1} B^T y_N \ . \quad (16)$$

Whereas,

$$B = \begin{bmatrix} -\frac{1}{2}(X^{(1)}(1) + X^{(1)}(2)) & 1 \\ -\frac{1}{2}(X^{(1)}(2) + X^{(1)}(3)) & 1 \\ \vdots & \vdots \\ -\frac{1}{2}(X^{(1)}(n-1) + X^{(1)}(n)) & 1 \end{bmatrix},$$

$$y_N=[X^{(0)}(2), X^{(0)}(3),\cdots, X^{(0)}(n)]^T \ .$$

As the time interval is equal, when it reaches time point k+1, altogether k time intervals have passed. The solution of differential Equation (15) is:

$$\hat{X}^{(1)}(k+1) = (X^{(0)}(1) - \frac{u}{a})e^{-ak} + \frac{u}{a} \ . \quad (17)$$

When $k\to\infty$, $\hat{X}^{(1)}(k+1) \to \frac{u}{a}$, and $\frac{u}{a}$ is the total settlement.

The value calculated out through Gray Model is the result of one accumulated generating operation, and the actual settlement could only be worked out after return. The predicted settlement at time point k+1 is:

$$\begin{aligned} \hat{X}^{(1)}(k+1) &= \hat{X}^{(1)}(k+1) - \hat{X}^{(1)}(k) \\ &= (X^{(0)}(1) - \frac{u}{a})(e^{-a} - 1)e^{-a(k-1)} \end{aligned} \quad (18)$$

GM (1,1) model for settlement prediction requires observation data of equal time interval. However, the total settlement observation time span is long and time interval is not uniform in actual observation practice. In consideration of unequal time interval of the observation data, GM (1,1) model of unequal time interval could be established. Concerning the problem of unequal time interval, Lagrange interpolation, cubic spline interpolation and other methods could be applied to convert settlement sequences of unequal time interval to sequences of equal time interval.

2.2 Metabolism Model GM (1,1)

When GM (1,1) model is applied to predict bridge group piles foundation settlement, prediction accuracy becomes worse and worse as time goes by. The major reason is that GM (1,1) model is based on gray model. The gray plane extends in trumpet shape, and the further away from the time point is, the bigger the prediction gray area becomes. Therefore, improvements should be made on this basis.

As settlement measurement is carried out periodically, new observation data are taken continuously, which will enrich the time sequence data. The model established with supplemented new data is called metabolism model. Metabolism GM (1,1) model uses known sequence to establish GM (1,1) model to predict the next value; this predicted value will be supplemented to the known sequence, and the first datum will be removed at the same time to maintain equal dimension; then a new GM (1,1) model will be established to predict the next value; prediction will be carried out this way step by step.

Situation on site is always changing. Although the measurement data obtained in earlier time play a certain role in the study of settlement, which will take place in later time, if compared with newly measured data, the latter is more helpful in showing the new tendency and change of settlement. Therefore, in order to avoid increase of sequence length, while adding in a new datum, the first known datum should be removed at the same time. The prediction accuracy of equal dimension metabolism model has been proven higher than that of whole sequence model by a large number of modeling prediction practices.

3. APPLICATION IN ENGINEERING PRACTICE

This paper will take the group piles foundation of one pier from Yunzaobang major bridge, Shanghai-Nanjing section of Shanghai-Beijing high speed railway, as an example.

Yunzaobang major bridge crosses a group of bridges of Wusong River, where 6 bridges of 10 lanes go parallelly. The construction of long span continuous beams requires complex processes. Cast-in-situ method is adopted for the construction of a large number of proposed simply supported beams instead of precast and machine laying method. This section involves complex structural stress and is the key part of settlement monitoring.

The calculation parameters are shown as follows: Pile cap size 8.5m×10.2m^3, 12 (3×4) nos of bored piles, pile diameter 1.0m, pile length 43.0m, pile longitudinal space 2.7m, transverse space 3.2m. The stratum distribution and soil physical and mechanical parameters are shown in Table 1.

Table 1
Stratum Distribution and Soil Physical and Mechanical Parameters of One Pier of Yunzaobang Major Bridge

Soil name	1st layer plain fill	2nd layer silty sand clay	3rd layer silty clay	4th layer silty soil	5th layer silty clay	6th layer silty sand
Soil state	slightly wet	flow plastic	hard plastic	medium dense, saturated	soft plastic	medium dense, saturate
Top elevation (m)	0	-1.38	-3.82	-10.82	-16.32	-22.57
Bulk density (kN/m^3)	9.2	7.8	10.3	8.7	8.7	9.0
Cohesion (kPa)	24.5	8.4	57.3	15.6	14.7	5.0
Internal friction angle (°)	8.7	6.4	16.7	15.0	15.3	20.0
Compressive modulus (MPa)	4.61	4.35	13.86	10.01	6.08	16.00
Permeability coefficient (m/s)	0.52×10^{-9}	0.97×10^{-9}	0.63×10^{-9}	1.70×10^{-9}	1.24×10^{-9}	0.51×10^{-8}
Consolidation coefficient (m^2/s)	1.24×10^{-7}	2.24×10^{-7}	5.47×10^{-7}	11.38×10^{-7}	7.82×10^{-7}	\

According to the soil parameters and observation data from site, the calculation result and prediction analysis of the group piles foundation settlement of this pier is shown in Figure 2.

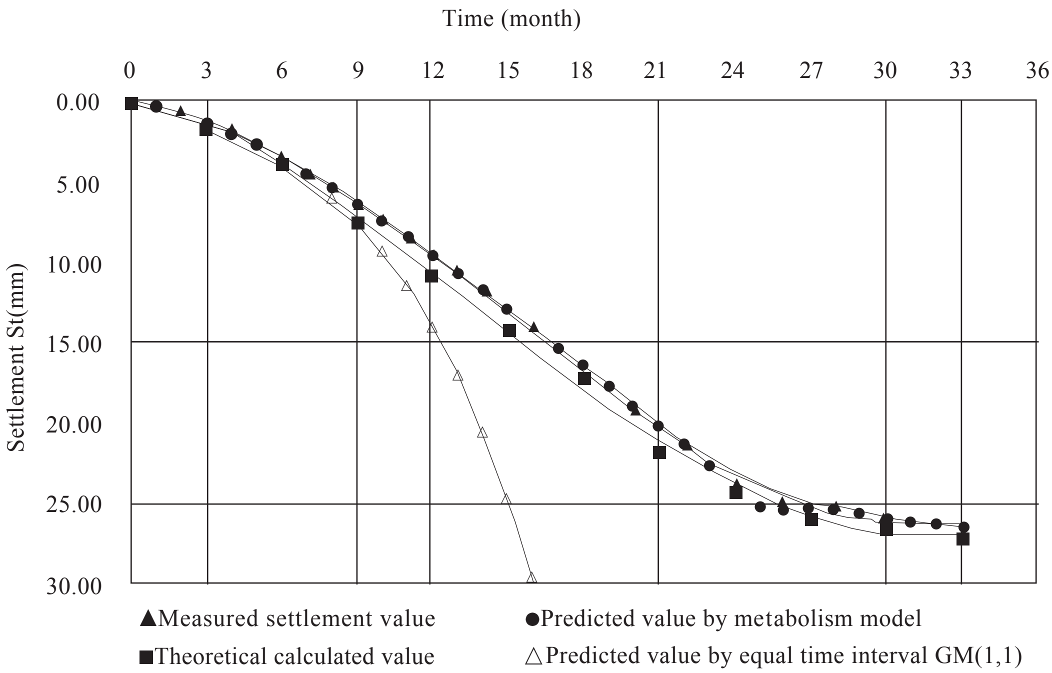

Figure 2
Comparison of Settlement Value by Site Measurement, Calculation and Prediction of One Pier of Yunzaobang Major Bridge

CONCLUSION

Post-construction settlement of high speed train bridge group piles foundation is one of the subjects that attract much attention from engineers in engineering practice. It is also a very complicated theoretical subject. As shown in Figure 2, the settlement tendency indicated by theoretical calculation is basically consistent with measured value, the difference between which is about 5%, indicating the comparability of the former with the latter; the predicted value by metabolism GM (1,1) model is in excellent agreement with measurement value, which proves the practicability of the prediction method stated in this paper. After analysis, it is concluded that :

(a) This paper made a theoretical analysis of the relationship between the change of group piles foundation post-construction settlement and time, and the calculation formula is deduced. Through comparative analysis with settlement observation data, it is shown that the calculated settlement value is slightly bigger than the measured value, and could meet requirements of engineering practice.

(b) This paper applied Gray Theory in post-construction settlement prediction for group piles foundation. The fitting result of measured settlement value with GM (1,1) model of equal time interval and with improved metabolism model shows that, the former is in good agreement with measured value at the beginning period, but diverges quickly with lapse of time and becomes obviously impracticable for mid and later prediction period; fitting of predicted settlement value by the latter with measured value is excellent, and the establishment of dynamic prediction model through newly supplemented observation data reflects the new changes of settlement, which proves higher prediction accuracy and is much closer to measured value. Therefore, metabolism GM (1,1) model has good practicability in prediction of group piles foundation settlement. It will shorten construction period, reduce cost and improve quality by the application of Gray Theory in settlement prediction.

(c) In consideration of the difficulty of parameter selection in post-construction settlement calculation, this paper chooses ideal elastic-plastic model. It requires less parameters and the parameters are easy to determine. However, the construction site is in soft soil area. The creep properties of soft soil should be taken into consideration and it is necessary to select soft soil creep model for soil body analysis, so that the change process of load/settlement with lapse of time will be considered more reasonabe.

(d) Gray theory could make good prediction for post-construction settlement of group piles foundation and could provide reliable reference for high speed railway design and construction. As the study in the calculation and prediction of group piles foundation post-construction settlement is not much, the method proposed in this paper needs further test in other engineering practices.

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