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95 學年度博士班招生入學考試試題

所別：工程科技研究所
科目：工程數學 (甲)

1. Consider the damped forced motion governed by (15%)

$$\frac{d^2y}{dt^2}+2\frac{dy}{dt}+4y=\cos(\omega t)$$

in which ω is a positive real constant. Determine the value of the constant ω so that the maximum amplitude of the steady-state solution is achieved.

2. Consider the system of differential equations and initial conditions for the functions $x(t)$ and $y(t)$: (20%)

$$x'+y=t,$$

$$4x+y'=0,$$

$$x(0)=1, \quad y(0)=0.$$

Use the Laplace transform to solve the given initial value problem.

3. Let $f(x)=x-2\sin(x)+2\cos(3x)+\sin(4x)-\cos(5x)$ for $-\pi\le x\le\pi$. Find the Fourier series of f on the interval $[-\pi,\pi]$. (15%)

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4. (30%)

(1) Please find the projection of vector $\vec{A} = 3\vec{i} + \vec{j} + 5\vec{k}$ on the direction of vector $\vec{B} = \vec{i} + \vec{j} + \vec{k}$

(2) Please find the projection of vector $\vec{A} = 3\vec{i} + \vec{j} + 5\vec{k}$ on the plane of $x + y + z = 0$.

(3) Please find the angle between vector $\vec{A} = 3\vec{i} + \vec{j} + 5\vec{k}$ on the plane of $x + y + z = 0$.

5. (20%)

Find general solution u(x,y) of the following partial differential equation.

$$u_x + u_y = (x + y)u$$

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每題 10 分，總計 100 分

1. Evaluate $\iint_{\Sigma} f(x,y,z)d\sigma$, if $f(x,y,z)=z$, Σ the part of the cone $z=\sqrt{x^2+y^2}$ lying in the first octant and between the planes z = 2 and z = 4.

2. Evaluate $\iint_{\Sigma} F \cdot N d\sigma$, if $F=4x\vec{i}-z\vec{j}+x\vec{k}$, Σ the hemisphere $x^2+y^2+z^2=1,\ z\ge 0$, including the base consisting of points (x,y) with $x^2+y^2\le 1$.

3. Evaluate $\oint_C F \cdot dR$, if $F=xy\vec{i}+yz\vec{j}+zx\vec{k}$, Σ the part of the plane $2x+4y+z=8$.

4. Find the determinant of the matrix $A=\begin{bmatrix} 22 & -1 & 3 & 0 & 0 \\ 1 & 4 & -5 & 0 & 2 \\ -1 & 1 & 6 & 0 & -5 \\ 4 & 7 & 9 & 1 & -7 \\ 6 & 6 & -3 & 4 & 1 \end{bmatrix}$.

5. If matrix $A=\begin{bmatrix} 5 & -4 & 4 \\ 12 & -11 & 12 \\ 4 & -4 & 5 \end{bmatrix}$, please find

(a) eigenvalues
(b) eigenvector
(c) matrix p diagonalizes A.

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95學年度博士班招生入學考試試題

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6. solve $y' - 2xy = x^2 + y^2$

7. solve $4y'' + 36y = \csc 3x$

8. Find the general solution $y(x)$ of the following differential equation.

$$y'' - (y')^2 = 0$$

9. A periodic function whose definition in one period is

$$f(t) = 3\sin\frac{\pi t}{2} + 5\sin 3\pi t \;,\; -2<t<2 \;,$$

(a) Find the Fourier series of $f(t)$.
(b) Find the Fourier transformation of $f(t)$.

10. Solve the following first order differential equation by applying the Fourier transform $y' - 2y = e^{-2t}u(t)$, $-\infty < t < \infty$, where $u(t)$ is the unit step function.

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1. Find the general solution for the following differential equations (25%)

(1) $\frac{dy}{dx} = 2xy^2$.(5%)

(2) $1 + \left(3x - e^{-2y}\right)\frac{dy}{dx} = 0$ *[Hint: Try integrating factor* e^{ay} *]* (5%)

(3) $\frac{dy}{dx} + \frac{1}{x}y = -y^2$ *[Hint: Bernoulli equation]* (5%)

(4) $y'' - y' - 20y = 0$ (5%)

(5) $x^2 y'' - 5xy' - 6y = 2\ln(x)$ *[Hint: Euler's equation]* (5%)

2. The homogeneous system of linear equations $AX = 0$, in which

$$A = \begin{bmatrix} 5 & 0 & 1 & 0 \\ 0 & 0 & 0 & 3 \\ 0 & 0 & 1 & 6 \\ 0 & 4 & 0 & 0 \end{bmatrix}.$$ Find (15%)

(1) the reduced row echelon form (A_R) of A and produce a matrix Ω such that $\Omega A = A_R$,(5%)

(2) the determinant of A, $|A| = ?$,(5%)

(3) the general solution of $AX = 0$ (5%)

3. Find a fundamental matrix $\Omega(t)$ and the general solution $X(t) = \Omega(t)C$ for the system of linear differential equation

$$\begin{aligned} \frac{dx_1}{dt} &= 4x_1 + 2x_2 \\ \frac{dx_2}{dt} &= 3x_1 + 3x_2 \end{aligned}$$ 。 (10%)

4. Find the Laplace transform for the following function (10%)

$[\cos(t-1) + (t^2 - 1)]H(t-1)$, where H(t) is Heaviside function.

5. Find the inverse Laplace transform for the following functions. (20%)

(a) $\ln[(s-1)/(s+1)]$ (10%)

(b) $\frac{se^{-2s}}{(s+1)^2(s^2+4s+5)}$ (10%)

6. Find the sum of the series $\sum_{n=1}^{\infty} (-1)^n / (4n^2 - 1)$. (10%)

(hint :expand sin(x) in a Fourier cosine series on [0 π] and choose an appropriate value of x.)

7. Find the inverse Fourier transform for function: $\frac{5e^{2(\omega-1)i}}{[3 + (\omega - 1)i]}$. (10%)

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請從後面兩個附件中，選讀其中之一，然後針對所選讀的附件回答下列各問題。(附件 1 結構工程與材料領域：第 2 至 11 頁、附件 2 營建管理領域：第 12 至 24 頁)。請清楚標明所選讀之附件編號。

請依下列四點評論：

(1) 本篇文獻之背景與研究目的。(25%)

(2) 本篇文獻之研究方法。(25%)

(3) 本篇文獻之具體貢獻。(25%)

(4) 本篇文獻之缺點與限制。(25%)

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Influence of modeling assumptions on the seismic response of multi-span simply supported steel girder bridges in moderate seismic zones

Bryant G. Nielson, Reginald DesRoches*

School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0355, United States

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Abstract

Steel girder bridges are one of the most common bridge types in the central and south-eastern United States (CSUS). An understanding of their seismic response and assessment of their seismic risk has become a focus of the earthquake engineering community due to the increased awareness of the seismic hazard in the region. Analytical assessment of this seismic risk requires an evaluation of typical seismic responses and more of an understanding of the modeling parameters that significantly affect those responses. A seismic evaluation of a typical configuration for a multi-span simply supported steel girder bridge is performed for an approximate hazard level of 2% in 50 years using a nonlinear three-dimensional (3-D) analytical model. The results show significant vulnerabilities in the reinforced concrete columns and in the steel fixed and expansion bearings. Although the longitudinal loading of the bridge results in much larger demands compared with the transverse loading, some components of the bridge may still have appreciable damage under the transverse loading case. An analytical design-of-experiments screening study shows that modeling parameters such as loading direction and damping ratio are the most important in determining seismic response. Fixed bearing stiffness, among others, also significantly affects the response and should be considered carefully.

Keywords: Steel bridges; Bridge bearings; Seismic response; Seismic analysis; Sensitivity; Modeling parameters inventory analysis

1. Introduction

During the period from the 1950s through the 1980s, many of the highway bridges built in the central and south-eastern United States (CSUS) were built using a concrete slab-on-steel girder construction. Many of these bridges are still in operation and account for over one third of all bridges in the region today [1]. In general, seismic consideration was not given to the design of these bridges until after 1990 [2]. However, a heightened awareness of the seismic hazard that is present in the region has developed over the last decade and a half, and has raised concern over their seismic vulnerability.

This increased concern over the seismic hazard in the CSUS has caused state departments of transportation and researchers to examine the seismic risk to this portfolio of steel bridges more closely. This is particularly applicable to steel bridges that employ the use of steel fixed and rocker bearings, as previous research has shown them to be largely deficient under seismic loading [3]. Probabilistic vulnerability functions are becoming increasingly popular tools for assessing this risk [4]. To derive these vulnerability functions, particularly for the CSUS, detailed analytical models must be developed. The complexity of such models can range from very simplistic, consisting of only a few degrees-of-freedom with linear component modeling, to very detailed, where nonlinear behavior is modeled throughout the various bridge components. The appropriate level of modeling is dependent on the bridge configuration, bridge type, seismic demand and the response that is anticipated. Modeling issues such as two-dimensional (2-D) versus three-dimensional (3-D), transverse versus longitudinal, and linear versus nonlinear often arise. These types of issues can more appropriately be addressed as an understanding of the effect of different modeling assumptions is attained.

There have been a number of studies to date that have been tailored to improve our knowledge concerning the modeling and response of steel girder bridges. In one study, Dicleli

* Corresponding author. Tel.: +1 404 385 0826; fax: +1 404 894 0221.
E-mail addresses: bryant.nielson@ce.gatech.edu (B.G. Nielson), reginald.desroches@ce.gatech.edu (R. DesRoches).

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and Bruneau [5] investigated the response of multi-span simply supported (MSSS) steel girder bridges using linear 3-D analytical models. They explored such issues as loading direction (longitudinal and transverse), bearing stiffness and column behavior using linear elastic response spectra analyses. One significant conclusion of this study is that the stiffness with which the steel bearings are modeled significantly affects the bridge response. In another study, they considered the response of both single-span and multiple-span continuous steel girder bridges [6]. Using both elastic linear and nonlinear inelastic dynamic analyses, they determined that damage to the steel bearings was likely. However, they also noted that, as long as stability was not lost, bearing damage is acceptable, since it would act as a fuse and limit the seismic demand placed on the columns. In addition, they concluded that transverse response is dominant for these bridge types. It has been recognized that full nonlinear time history analyses are required if the effects of deck pounding are to be considered.

In another study on MSSS steel girder bridges, Rashidi and Ala Saadeghvaziri [7] considered a three-span bridge that was analyzed in the longitudinal direction using a 2-D model. Linear elements were used to model column behavior, the fixed bearings followed a bilinear behavior, and gap elements were used to capture deck pounding. They concluded that it is important to consider the effects of pounding between decks to capture the post-yield behavior of the bearings. In a subsequent study, these researchers looked specifically at the effect the steel bearings had on the seismic response of highway bridges using 2-D models of the longitudinal and the transverse direction which did not include the effects of pounding. They came to the conclusion that the response of the bridge was highly dependent on the stiffness of the bearings when loaded in the transverse direction, but inconsequential when longitudinal loading is applied [8]. It should be noted that this finding is not consistent with that of Dicleli and Bruneau [5].

The modeling and responses for both simply supported and continuous span bridges were considered using 2-D longitudinal models in work performed by DesRoches et al. [9]. Using full nonlinear time history analyses and highly detailed modeling, they concluded that steel bearings are indeed susceptible to failure as a direct result of deck pounding. The reinforced concrete columns and the abutments also exhibited moderate levels of damage. None of these previous studies used 3-D models of multi-span simply supported steel girder bridges subjected to full nonlinear time history analyses incorporating the effects of pounding, nonlinear behavior in the steel bearings, and nonlinear behavior in the columns simultaneously.

The previous studies, among others, have been invaluable in acquiring an understanding pertaining to the response of steel girder bridges. However, there is still a need for a better understanding of issues such as the appropriate modeling dimension (3-D versus 2-D) and the significance of various modeling parameters on the responses of the various bridge components. In particular, a quantitative measure of the importance of modeling assumptions on the predicted behavior is needed. The first goal of this study is to understand better the effects of longitudinal versus transverse loading on the response of typical MSSS steel bridges and make inferences on appropriate modeling dimensions. The second goal is to determine the influence that various common modeling parameters have on the responses of the different bridge components. This is accomplished by using a detailed nonlinear 3-D model of a three-span MSSS Steel girder bridge and performing a "design of experiments" screening study on 14 structural parameters. Prior to the presentation of this screening study, a discussion of typical deterministic responses for this bridge type is provided.

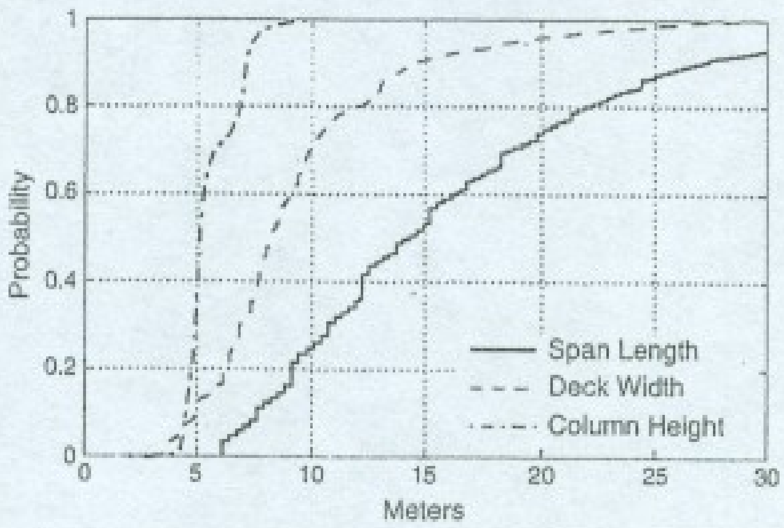

Fig. 1. Empirical CDFs for bridge geometry.

2. Characteristics of typical multi-span simply supported steel girder bridges

A detailed review of the steel girder bridges in the national bridge inventory (NBI) shows that simply supported multi-span bridges account for approximately one third of all steel girder bridges [1]. The other two thirds are equally split between single span and continuous multi-span bridges. Of the MSSS steel girder bridges, over 90% were built prior to 1990, implying a lack of seismic design and also highlighting their relatively small use in current construction. To give an idea of the typical geometric properties of this bridge class, empirical cumulative distribution functions (CDFs) are generated and shown in Fig. 1. Over 90% of the MSSS steel girder bridges fall in the range of 6–30 m. The 90th percentile value for bridge width and column height are around 15 m and 7 m, respectively. The range for the number of spans is from 2 to 19, with 90% of all bridges being in the range of 2 to 5 spans. The most likely number of spans is 3, which represents 44% of the entire class. Bridge skew is 0° for over 60% of the bridges and is less than 30° for greater than 87%.

Typical details for these bridges are determined from several previous studies, one of which examined over 150 detailed sets of bridge plans [10]. These bridges primarily used one of two general classes of steel bearings, namely high-type and low-type. The high-type bearing class includes a fixed (pinned) type and an expansion (rocker) type. The same is typical of the low-type bearings, other than the expansion bearing motion is typically defined as sliding rather than rocking. Other standard details for the bridge substructure are outlined in a study by Hwang et al. [11] on bridges in Memphis, TN as follows:

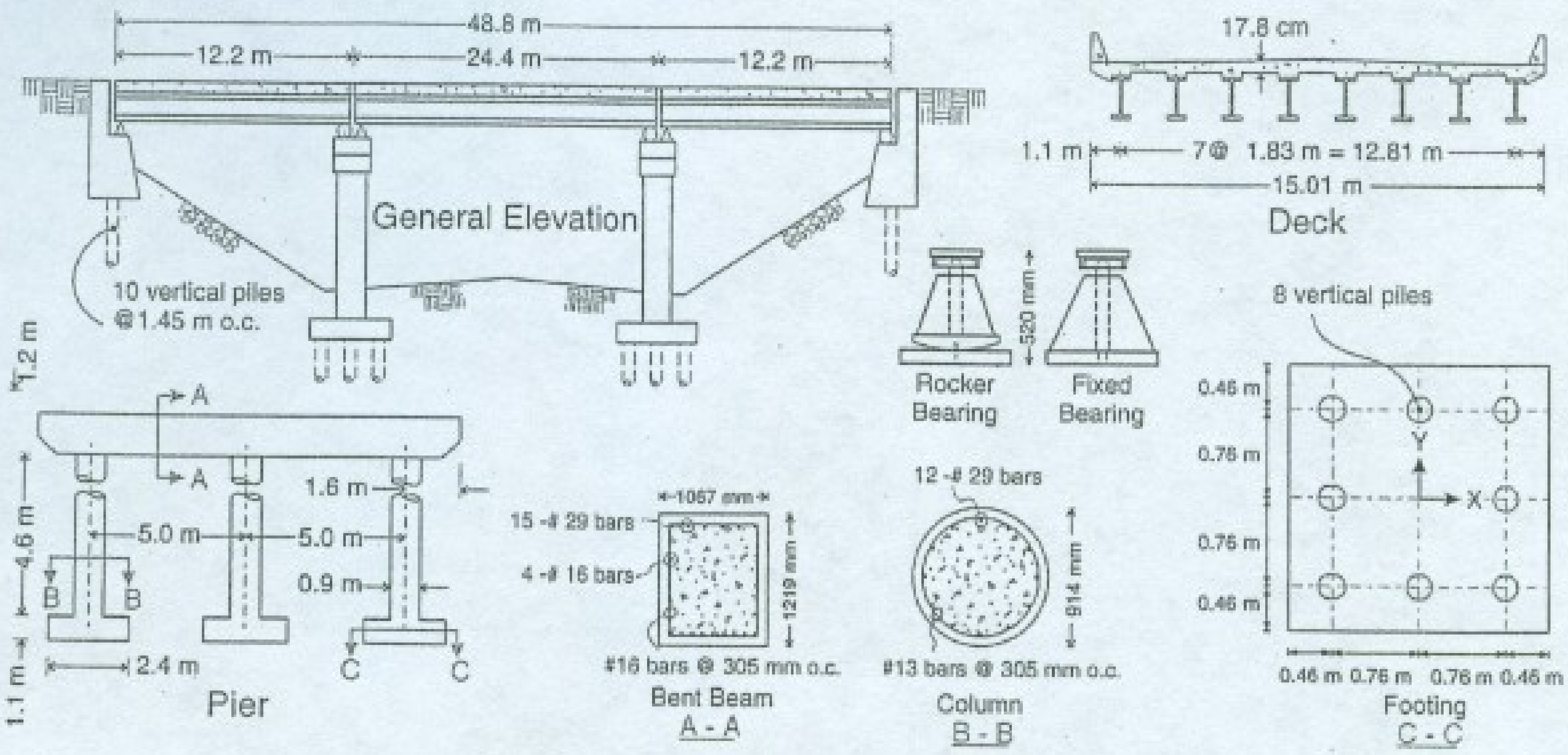

Fig. 2. Configuration of typical MSSS steel girder bridge in CSUS.

- Multi-column bents are used where concrete columns are typically 914 mm in diameter with 1% vertical reinforcing and #10 or #13 transverse ties spaced at 305 mm.
- Lap splices in the vertical reinforcement of columns are placed in possible plastic hinge zones just above the pile cap.
- No hooks or bends are placed in a vertical column reinforcement that extends into the bent cap.
- Most bridges are founded on driven pile foundations with no positive connection between the piles and cap.

3. 3-D analytical modeling of multi-span simply supported steel girder bridge

Using data collected pertaining to the inventory of MSSS steel girder bridges in the CSUS, a typical bridge configuration with standard details is developed. Fig. 2 shows the geometric layout of the bridge used in this study. The bridge is characterized by three spans which have lengths of 12.2 m, 24.4 m, and 12.2 m for an overall bridge length of 48.8 m. The decks are 15 m wide with a skew of 0° and are constructed of eight steel girders that are supported by two pile bent abutments and two three-column bents. Each abutment configuration utilizes 10 vertical piles at 1.45 m on-center, while the square footing under each column has a symmetric layout of eight vertical piles.

Using the finite element analysis package OpenSees [12], a detailed 3-D nonlinear model of the bridge is created, as illustrated in Fig. 3. Nonlinearities are considered explicitly in the abutments, bearings, columns and bent caps. The superstructure, which refers to the composite slab and girder section, is expected to remain linear and is thus modeled using linear elastic beam–column elements. The deck section, which is transformed to an equivalent homogeneous steel material, has an elastic modulus of 200 GPa. Table 1 gives the elastic properties for both the end spans and the middle span, where A is the cross-sectional area, I_z is the moment of inertia about the horizontal transverse axis, and I_y is the moment of inertia about the vertical axis. The pounding between the decks is accounted for by using the contact element approach including the effects of hysteretic energy loss, which is outlined in the work by Muthukumar [13].

Table 1
Elastic properties of deck sections

Span location	A (m^2)	I_z (m^4)	I_y (m^4)	Weight (kN/m)
End	0.51	0.03	9.78	39.00
Center	0.68	0.11	13.00	52.00

The columns are modeled using displacement beam–column elements which are discretized into both steel and concrete fibers. Each fiber has a uniaxial stress–strain relationship representing either confined concrete, unconfined concrete, or longitudinal reinforcing steel. The individual fiber behaviors integrate to get a load–deformation relation for the composite reinforced concrete section. This distributed plasticity formulation permits monitoring of the column's nonlinear responses at various integration points along the length of the member, making it appropriate for modeling the reinforced concrete columns.

The steel bearings in this study are modeled in a nonlinear manner using translational springs. The behavior of the bearings in both the longitudinal and transverse directions follows the recommendations given by Mander et al. [3] which resulted from their experimental work on steel bearings. A frictional component of each bearing model exists which is a function of the normal force that is applied to them. This results in slightly different models for the end spans and the center span. Fig. 4 shows the hysteretic behavior of the two bearing types (fixed and rocker) in both the longitudinal and transverse directions for the center bridge span. These translational springs are connected between the abutment springs and deck nodes at the ends of the bridge. They are also used to connect the bent cap nodes with the deck nodes, as seen in Fig. 3.

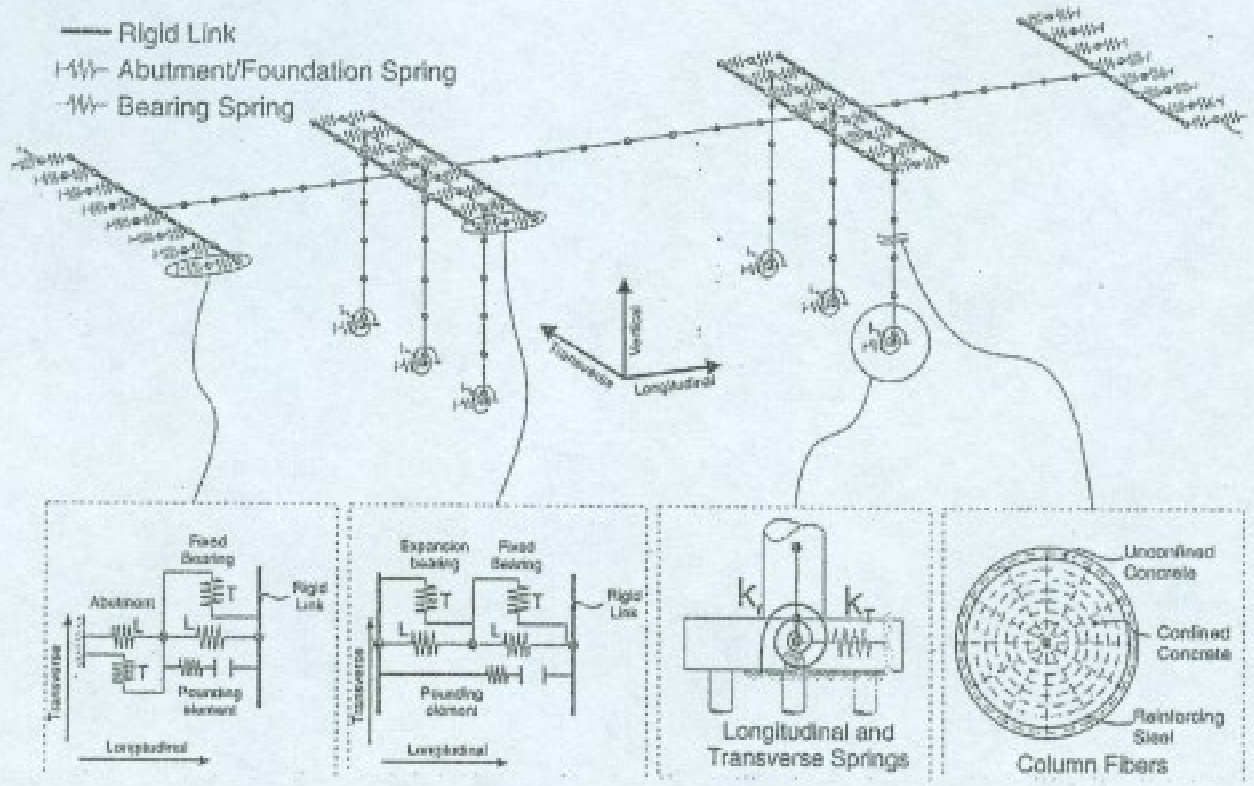

Fig. 3. Nonlinear analytical model of multi-span simply supported steel girder bridge including nonlinear elements used for abutments, bearings and columns.

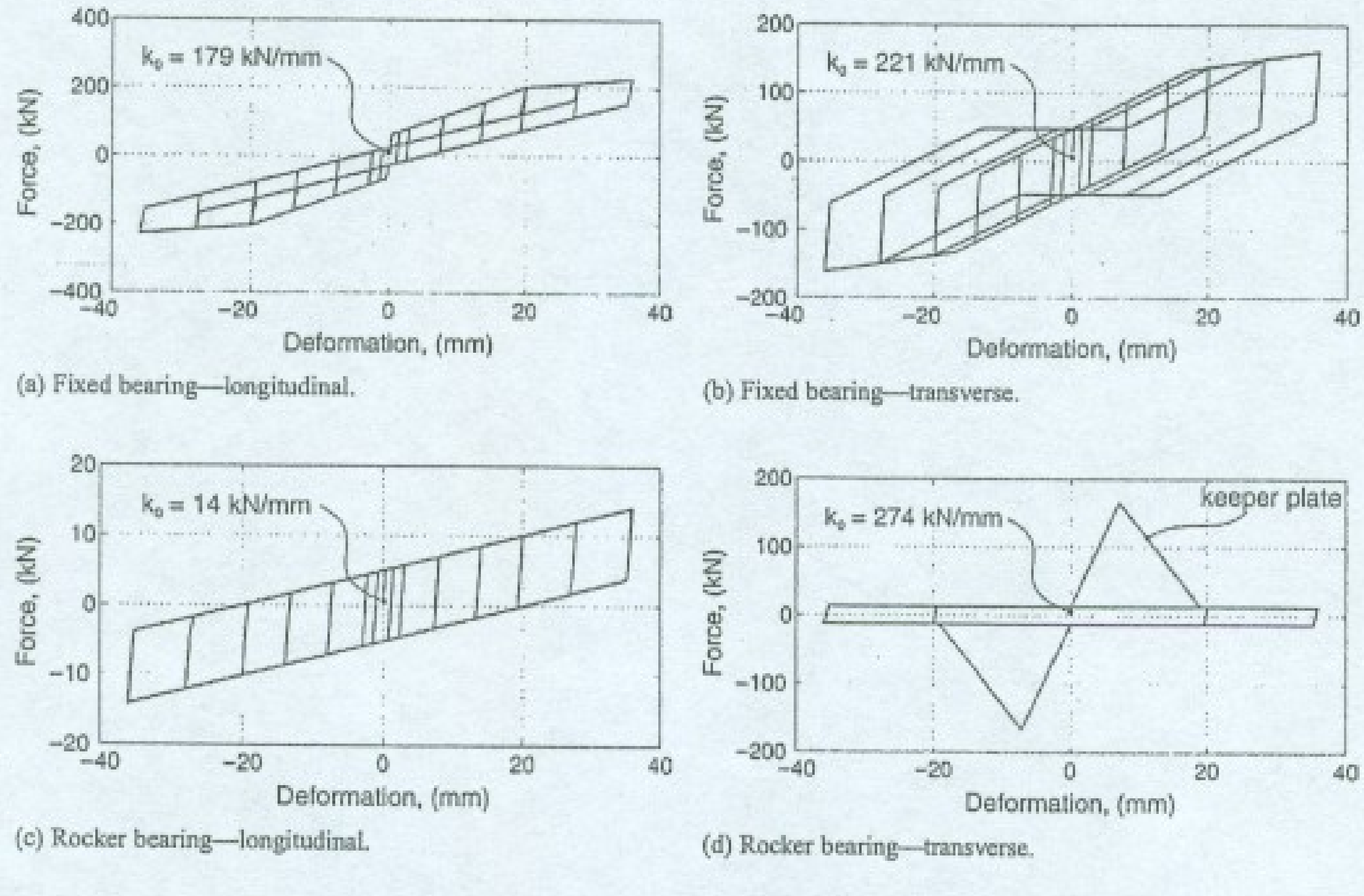

Fig. 4. Nonlinear analytical models of steel fixed and rocker bearings at center span [3].

The initial passive stiffness of abutments due to the soil is modeled with a value of 20.2 kN/mm/m width of wall. This is a mid-range value selected from the range of stiffnesses (11.5–28.8 kN/mm/m) recommended by Caltrans [14]. Furthermore, Caltrans also recommends that the ultimate soil pressure be assumed to be 0.37 MPa, which Martin and Yan [15] found occurs at a tip displacement of 6%–10% of the back-wall height. These recommendations were used to assemble a nonlinear backbone for soil stiffness as shown in Fig. 5. The contribution of the piles was added using a lateral stiffness of 7 kN/mm/pile, as recommended by Caltrans [14]. The model considers both soil and pile contributions in the passive (compression) direction, but only considers the contribution of the piles when loaded in the active (tension) direction. The model for the transverse behavior uses a conservative approach, in that it neglects the contribution of the wing walls and only considers the stiffness of the piles.

The stiffness of the pile foundation is accounted for by using both translational and rotational linear springs at the base of the columns. The spring constants were calculated for the footing and pile configuration shown in Fig. 2. Lateral pile stiffnesses were assumed at 7 kN/mm/pile [14] and the vertical stiffnesses

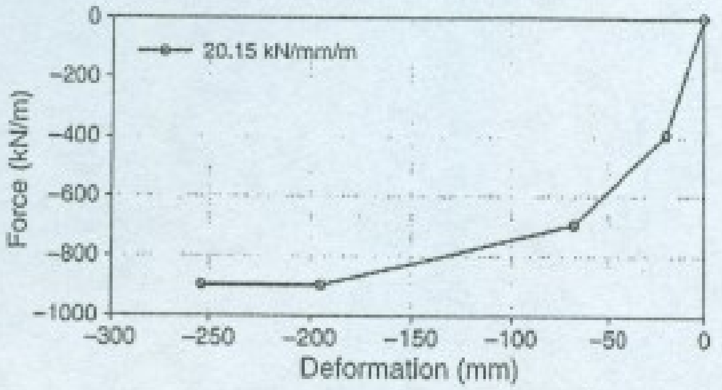

Fig. 5. Nonlinear analytical model of abutment back-fill (passive soil).

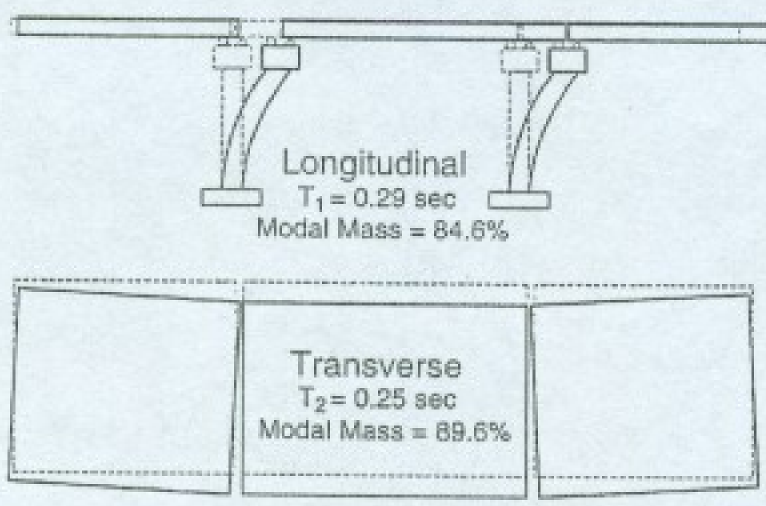

Fig. 6. Fundamental modes of bridge.

Table 2
Modal bridge properties

Number of mode	Period (s)	Effective modal mass		
		Longitudinal (%)	Transverse (%)	Vertical (%)
First	0.29	84.6	1.1	0.0
Second	0.25	1.0	89.6	0.0
Third	0.23	0.0	0.0	31.5
Fourth	0.18	0.0	0.4	0.0
Fifth	0.14	0.8	0.0	0.0

were assumed to be 175 kN/mm/pile [10]. This results in a translational spring constant of 56 kN/mm and a rotational spring constant of 6.09E5 kN m/rad.

4. Dynamic bridge characteristics

The basic modal properties for the bridge are presented in Table 2. It is noted that the fundamental mode is a longitudinal mode with a period of 0.29 s and an effective modal mass of 84.6%. The second mode is transverse with a period of 0.25 s and an effective modal mass of 89.6%. The left most deck in Fig. 2 is tied into the left abutment with a relatively stiff fixed bearing. The other end of this span is tied to the left most bent with a fairly flexible expansion bearing. This causes there to be somewhat of a disconnect between the left span and the rest of the bridge. This phenomenon is seen through examination of the fundamental mode shape of this bridge, as given in Fig. 6.

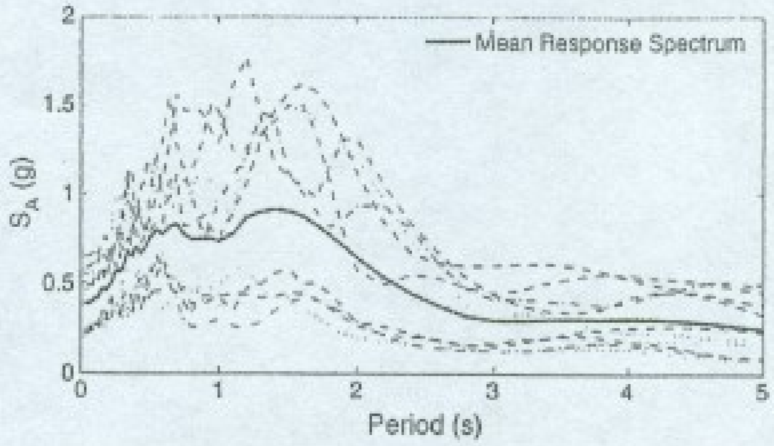

Fig. 7. Mean response spectrum for ground motion suite.

5. Seismic response

The seismic response of this bridge is evaluated using a suite of synthetic ground motions developed as part of ongoing research in the Mid-America Earthquake (MAE) Center. Rix and Fernandez-Leon [16] generated several deterministic ground motions for Memphis, TN that consider the effects of source, path and site. The records were generated for three different magnitudes (5.5, 6.5, 7.5) and four hypocentral distances (10, 20, 50 and 100 km). For the purposes of this study, 10 of these ground motions are selected such that they approximately represent a seismic hazard of 2% in 50 years. A seismic hazard disaggregation of the Memphis area revealed a modal distance and magnitude for this seismic hazard level to be 32.8 and 7.7, respectively [17]. Therefore five ground motions are selected from the 7.5–20 km bin and five are selected from the 7.5–50 km bin. The range of peak ground acceleration (PGA) values for this suite is from $0.22g$ to $0.65g$. A plot of the acceleration response spectra, including the mean response spectrum for the ground motion suite, is given in Fig. 7.

This suite of ground motions is applied to the subject bridge in the principal orthogonal axes—longitudinal and transverse. A few select responses for this bridge subjected to the $0.65g$ earthquake, which has a magnitude and hypocentral distance of 7.5 and 20 respectively, are discussed below. A plot of the longitudinal displacement response of the three decks under longitudinal loading, as shown in Fig. 8, highlights once again the stiffness difference between the left deck and the rest of the bridge. Displacements for the middle and right most decks peak at around 75.0 mm, while the left most deck has a maximum displacement of approximately 45.0 mm. In the transverse direction under transverse loading, the displacements are relatively equal, with a peak of approximately 40.0 mm.

The fixed bearings located at the left abutment appears to experience the largest deformation of the three bearing locations. Representative responses of these bearings under both loading conditions are given in Fig. 9, where maximum deformation in the longitudinal direction is around 38.0 mm and 10.0 mm in the transverse direction. Column responses are given in terms of curvature ductilities. As seen in Fig. 10, longitudinal loading results in curvature ductilities of $\mu = 2.0$, while the transverse loading is approximately $\mu = 1.0$. The expansion bearings have maximum deformations approaching

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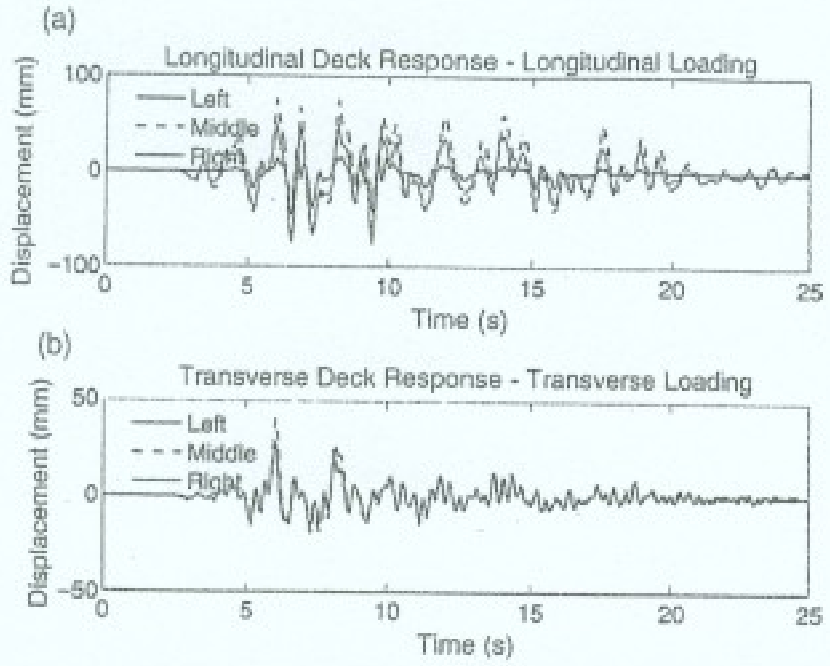


Fig. 8. Displacement time histories of bridge decks: (a) longitudinal response—longitudinal loading; and (b) transverse response—transverse loading.

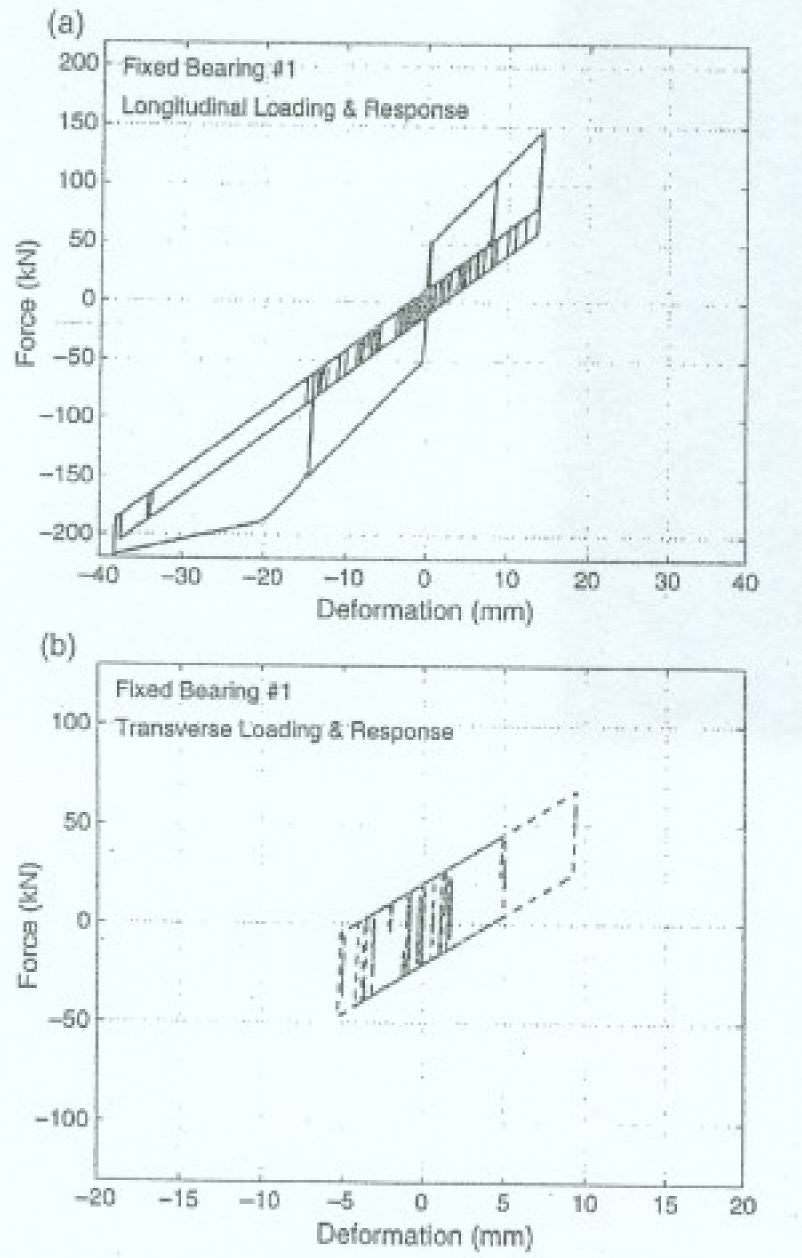


Fig. 9. Fixed bearing response at left abutment: (a) longitudinal loading and response; and (b) transverse loading and response.

80.0 mm in the longitudinal direction, but less than 5.0 mm in the transverse direction. The abutments for the most part remain linear in both directions through the loading sequence.

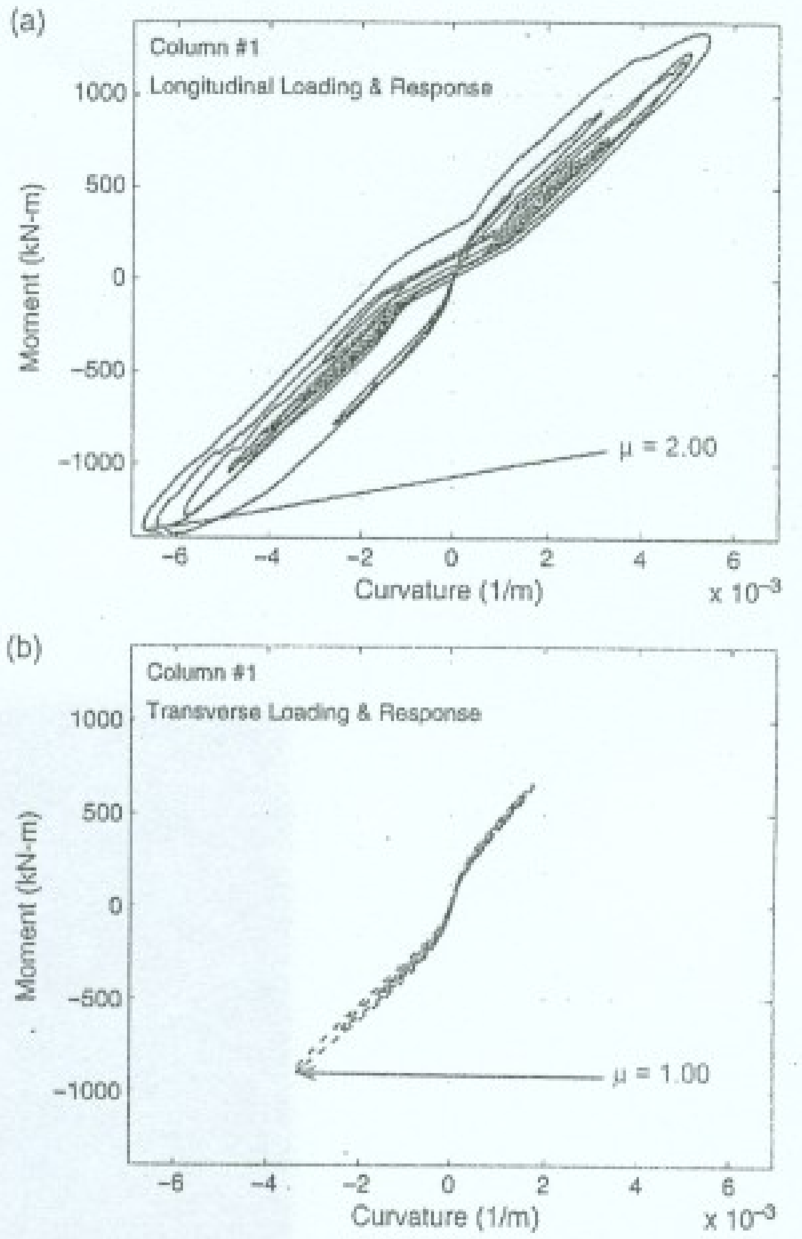
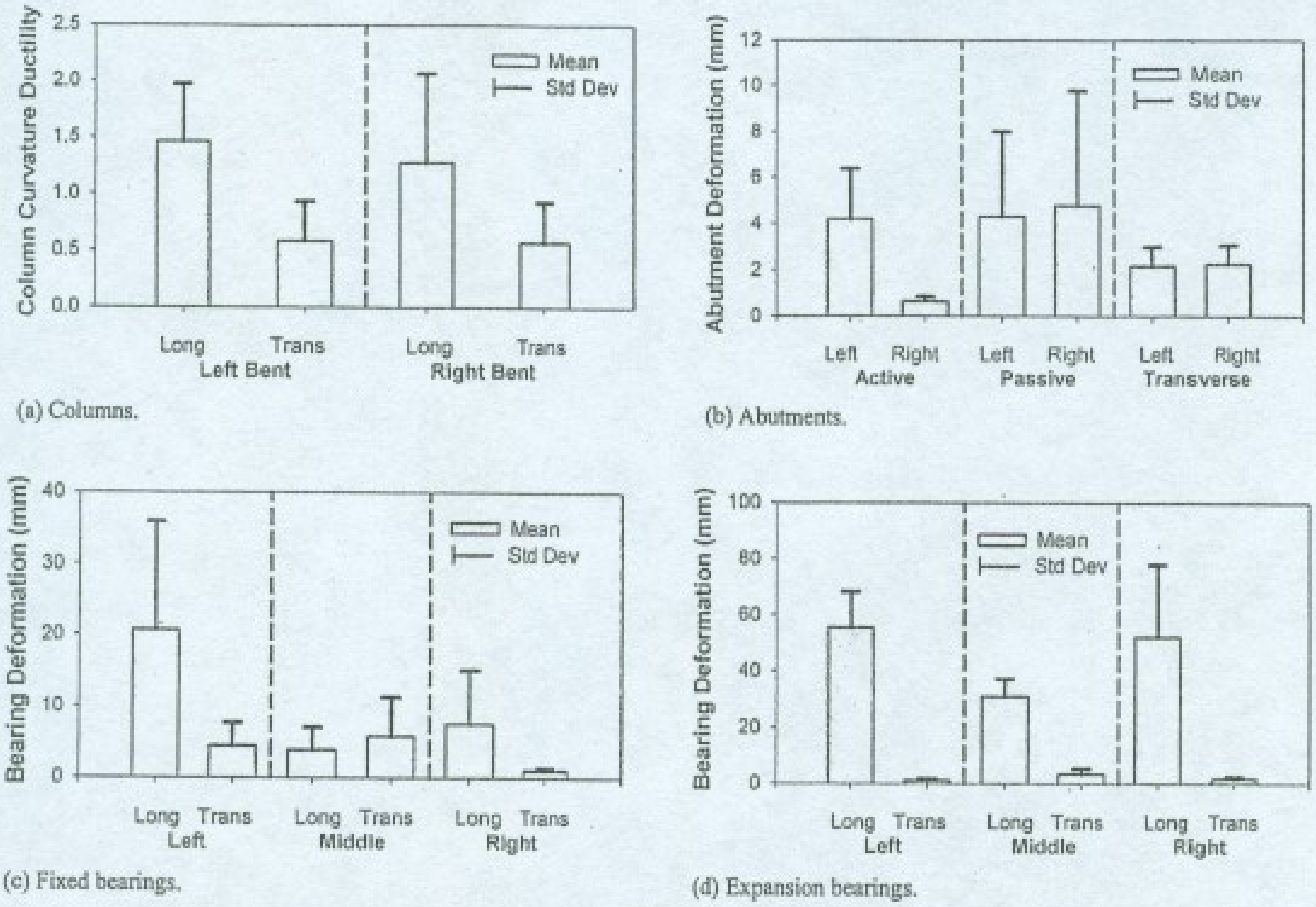


Fig. 10. Curvature ductility demand for columns in left bent: (a) longitudinal loading; and (b) transverse loading.

A better understanding of the seismic response of this bridge type is obtained by looking at the peak component responses for the entire ground motion suite. Fig. 11(a) shows the mean and mean-plus-one standard deviation for ductility demands in the columns. The columns of the left bent have an average ductility of $\mu = 1.4$ under longitudinal loading, while the right columns have a slightly lower average of $\mu = 1.3$. The transverse loading scenario caused ductility demands for both the left and right columns that are less than half those for the longitudinal case, which are approximately $\mu = 0.6$.

Fig. 11(b) shows the mean and mean-plus-one standard deviation for deformations in the active, passive and transverse action of the abutments. The active action of the left abutment is significantly larger than that of the right abutment. This difference is largely due to the ability of their respective bearings to transfer loads to the abutments. This difference is not seen in the passive action, since this type of response is less dependent on bearing stiffnesses and more a function of pounding. Both abutments average passive deformations around 4.5 mm, which would not likely result in significant damage, based on research that has shown that slight damage would occur at deformations around 40 mm [18]. Transverse deformations are similar, with mean values around 2.2 mm.



(a) Columns.

(b) Abutments.

(c) Fixed bearings.

(d) Expansion bearings.

Fig. 11. Mean and mean-plus-one standard deviation of bridge responses to suite of ground motions.

Fixed bearing responses are summarized in Fig. 11(c), which shows the mean and mean-plus-one standard deviations of the deformations. It is clear that the left most bearings have the largest deformations, with a mean of 20.7 mm and a standard deviation of 15.2 mm. The tests on these bearing types by Mander et al. [3] show strength degradation at deformations of approximately 20.0 mm, which implies possible bearing failure. These large deformations are directly related to the fact that they are the primary lateral load resisting components for the left deck. The mean deformation for the rest of the bearings ranges between 1.0 mm and 7.5 mm.

Expansion bearing responses, as given in Fig. 11(d), show clearly that longitudinal loading causes a more dramatic degree of deformation than does transverse loading. This can be misleading, in that these rocker bearings are quite flexible in the longitudinal direction but quite stiff in the transverse direction. Hence, the deformation capacities in each direction would be starkly different as well. The mean deformations for the expansion bearings tied to the left and right decks are 55.5 mm and 52.3 mm respectively. Based on the work by Ala Saadeghvaziri and Rashidi [8], toppling of these rocker bearings is a concern when longitudinal movement exceeds $0.285R$, where R is the radius of the rocking surface. For these bearings, the radii are 330 mm, giving a stability boundary of 94.0 mm which was exceeded for some of the ground motions, thus indicating the potential for toppling of the bearing and potential unseating of the span.

The responses in a number of the components show a large degree of variation which is largely seen under longitudinal excitation. The bridge columns, the abutments in passive action and the bearings located at the abutments all appear to exhibit these significant variations. This variation is indicative of the highly nonlinear behavior of the components and the need to model them with a reasonable degree of fidelity. For example, under longitudinal loading the columns in both bridges show that their responses are highly variable, with coefficients of variation as high as 0.67. If the columns were modeled as being linear or even bilinear, it would be difficult to capture this variation. The variations, as seen in the transverse bearings of the MSSS girder bridge, also lend strength to the recommendation of analyzing these bridge types in both principal axes.

6. Modeling parameter significance screening

There are many parameters that go into defining the analytical bridge model developed as part of this study. These parameters may be geometric in nature, such as span length and column height, or they may help define material or component behavior, such as concrete strength and bearing stiffness. Experience suggests that the values these parameters assume in real life will vary from structure to structure and may also vary over time, which is a prime source of uncertainty in predicting seismic demand on the bridge. Being able to track this uncertainty and understand its impact on expected seismic responses is key to making informed decisions and inferences regarding seismic risk to existing bridges. This uncertainty is often quantified and tracked through the generation of probabilistic seismic demand models (PSDMs) which describe the probability of reaching or exceeding some

Table 3
Geometric bridge samples of MSSS steel girder bridge

Bridge no.	Spans	Middle span length (m)	Deck width (m)	Column height (m)
1	3	18.30	9.53	5.10
2	3	20.40	9.53	3.62
3	3	15.50	9.53	5.95
4	3	13.70	9.53	4.02
5	3	25.60	20.96	3.54
6	3	7.30	9.53	3.90
7	3	8.80	9.53	4.26
8	3	10.40	15.25	6.62

level of demand for a given intensity level of ground motion. Two types of uncertainty are captured in these probabilistic models, namely aleatoric (inherent randomness) and epistemic (lack of knowledge) [19]. The variation that occurs in the bridge modeling parameters is primarily considered to be epistemic in nature, as it is often based on our lack of exact knowledge of material properties, geometry, etc. It is very useful to know which of the common modeling parameters contribute in a significant way to the overall epistemic uncertainty associated with the seismic demand on this bridge, which can be obtained through an impact screening study of each of the parameters.

Eight different geometric configurations, representative of the CSUS bridge inventory for this bridge type, are generated from the inventory data presented in Fig. 1 using a Latin Hypercube sampling technique [20]. These eight configurations, which are given in Table 3, are then implemented in a "design of experiments" screening method to ascertain the significance of 14 different modeling parameters. A two-level fractional factorial screening design, considering main effects only, is set up considering the parameters and associated parameter levels as presented in Table 4. The parameter levels expressed in percentages imply that a percentage of the base value, which is assumed to be a median value, is used. The idea behind such a scheme is to select reasonable upper and lower values that each parameter could assume, then create different bridge samples through various permutations on those parameter values. Once these bridge samples are created, they are subjected to seismic loadings, after which a statistical analysis is performed to see which parameters appear to have the greatest impact on the response of the bridge.

Eight different responses are monitored from which to test the significance of each parameter. The responses are the curvature ductility of columns, deformations of fixed and expansion bearings in both the transverse and longitudinal directions, the passive and active deformations of the abutments, as well as the transverse deformation of the abutments. Using three different ground motions from Rix and Fernandez-Leon [16] and a screening design provided by a commercial statistical software package [21], the bridge models are analyzed using a full nonlinear time history analysis. An analysis of variance (ANOVA) of each of the eight responses was conducted to explore the effect each parameter has on each response. The ANOVA includes a hypothesis test that tests each parameter for significance in the model. The results of the hypothesis tests are given in terms of a p-value which can be interpreted using some selected significance level α. The general formulation of the entire ANOVA table, including the calculation of p-values, can be found in most texts on statistical analysis [22], while a more detailed formulation is found in [18]. A significance cutoff level of $\alpha = 0.05$ is used for this study, which means that any parameter that has a p-value less than 0.05 is deemed to be significant and should be treated with care.

Table 5 gives a list of the response-parameter combinations and their associated p-values as calculated from ANOVA. It is clearly seen from this table that the various measured responses are sensitive to different parameters. For instance, the curvature ductility value is sensitive to the strength of steel, the friction and stiffness of the fixed bearing, the damping ratio, and of course the direction of loading. However, looking at the longitudinal deformation of the expansion bearings, it is sensitive to the rotational stiffness of the foundations, the mass, the damping ratio, and also the loading direction. There are only two parameters, concrete strength and expansion bearing friction, that do not appear to be significant for at least one or more responses. One can also get a sense of the most important parameters based on the number of responses that a particular parameter significantly affects. For example, the loading direction is significant in the values of all eight responses and the damping ratio is significant for six. Other parameters, such as steel strength and passive stiffness of the abutments, are only significant in one response measure and therefore may not be as important as loading direction and damping ratio. The parameters are listed in Table 5 in a ranked order on the basis of the number of responses for which they are significant. It should be noted that the number of parameters that are classified as significant depends on the level of significance, α, that is chosen. Therefore it can be useful to also take a look at those parameter-response combinations whose p-values are close to the cutoff level. For example, the p-value associated with the hinge gap size and the passive response of the abutment is 0.058. This is quite close to the the 0.05 level and could reasonably be considered significant.

7. Conclusions

This paper presents the results of the seismic evaluation and screening study for a multi-span simply supported steel girder bridge, which is typical to the central and south-eastern United States. A synthetic ground motion suite, developed specifically for the Memphis, TN area that approximates a 2% in 50 years hazard level, is used to evaluate the seismic response of this bridge. A number of important conclusions are drawn pertaining to the bridge component responses and the structural modeling parameters that affect them.

First, at a hazard level of 2% in 50 years, this bridge type exhibits several vulnerabilities. The fixed and expansion steel bearings experience deformations that could lead to their failure through fracture or toppling. A general understanding of this has led to the general discontinued use of this type of bearing in

Table 4
Parameters considered in the screening of MSSS steel girder bridges

Parameter no.	Description	Abbreviation	Lower level	Upper level	Units
1	Concrete strength	Conc Str	26.4	40.6	MPa
2	Steel strength	Steel Str	438.2	555.3	MPa
3	Coefficient of friction for expansion bearing	Exp Frict	50	150	%
4	Coefficient of friction for fixed bearing	Fxd Frict	50	150	%
5	Initial stiffness of fixed bearing	Fxd Stiff	80	120	%
6	Initial stiffness of passive abutment	Ab-Pas Stf	50	150	%
7	Initial stiffness of active abutment	Ab-Act Stf	50	150	%
8	Rotational stiffness of foundations	Fnd-Rot Stf	50	150	%
9	Translational stiffness of foundations	Fnd-Hor Stf	50	150	%
10	Mass	Mass	90	110	%
11	Damping ratio	Damp Ratio	0.02	0.08	ratio
12	Gap between abutments and decks	Abut Gap	28	48	mm
13	Gap between decks	Deck Gap	18	33	mm
14	Loading direction (Long or Trans)	Load Dir	L	T	

Table 5
The p-values, as calculated in ANOVA for MSSS steel bridge

Parameter	P-value							
	Ductility	Fxd-Tran	Fxd-Long	Exp-Tran	Exp-Long	Ab-Pass	Ab-Act	Ab-Tran
Load Dir	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.014**	**0.000**
Damp Ratio	**0.001**	**0.000**	**0.001**	**0.000**	**0.005**	**0.000**	0.349	0.130
Fxd Stiff	**0.006**	**0.000**	**0.039**	**0.001**	0.142	0.545	0.346	0.267
Fxd Frict	**0.001**	**0.000**	0.568	**0.019**	0.372	0.623	0.565	0.492
Ab-Act Stf	0.948	0.917	0.325	0.659	0.887	**0.048**	**0.000**	**0.000**
Mass	0.652	0.146	**0.002**	0.302	**0.010**	0.126	**0.010**	0.246
Fnd-Rot Stf	0.328	0.598	0.105	0.803	**0.034**	**0.018**	0.451	0.565
Abut Gap	0.664	**0.045**	0.266	**0.003**	0.183	0.308	0.392	0.751
Hinge Gap	0.788	**0.009**	0.538	**0.000**	0.894	0.058	0.720	0.110
Fnd-hor Stf	0.631	0.681	0.219	0.773	0.380	0.194	**0.024**	0.483
Ab-Pas Stf	0.720	0.890	0.180	0.949	0.478	**0.015**	0.906	0.516
Steel Str	**0.013**	0.768	0.671	0.602	0.828	0.484	0.655	0.827
Conc Str	0.367	0.719	0.319	0.564	0.580	0.960	0.233	0.560
Exp Frict	0.729	0.769	0.436	0.194	0.918	0.648	0.066	0.469

Bold faced numbers are less than 0.05 and considered indicative of significance.

new construction. The columns that are generally deficient in transverse steel and seismic detailing have curvature ductility demands that would likely cause cracking and spalling of the concrete and subsequently failure of the lap-splice located at the base of the columns. The abutment demands do not appear to be as significant as the other components and would likely not experience significant damage.

Subjecting this bridge to seismic loading along each of the two principal axes shows an increased vulnerability under longitudinal loading as compared to transverse loading. For example, curvature ductility demands on the columns in the longitudinal direction are in general more than twice those in the transverse direction. Fixed bearing deformations follow this same general trend, which is largely attributed to the presence of deck pounding under longitudinal loading and its absence otherwise. It is seen in this study that, for MSSS steel girder bridges with little-to-no skew, it may be appropriate to model them using only 2-D longitudinal models when performing deterministic studies. However, when probabilistic approaches are used to assess seismic vulnerability of these bridges, the transverse response can be significant, particularly in the steel fixed bearings. This type of analysis may warrant 3-D models to fully capture the response contribution of both directions.

The seismic response of this bridge type is sensitive to a number of different modeling parameters, among which damping ratio and loading direction appear to be the most important. The screening test also shows that bridge responses such as column ductility demand and bearing deformation are sensitive to the stiffness of the fixed bearings. This stiffness can be significantly different, depending on whether the bearings are high-type — as used in this study — or low-type. It is therefore recommended that analytical models of steel bearings be developed with care. It is also useful, when generating analytical models of this bridge type, to carefully define the responses that will be monitored. This will help to outline the generation of the remainder of the model, giving an indication of which parameter values require the most diligence when setting.

This study will make important contributions to the earthquake engineering community as they strive to accurately assess the seismic risk of transportation systems in the CSUS. A better understanding of seismic bridge response and modeling issues help researchers to estimate this risk more accurately.

Acknowledgments

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Non-Unit-Based Planning and Scheduling of Repetitive Construction Projects

Rong-yau Huang[1] and Kuo-Shun Sun[2]

Abstract: Repetitive scheduling methods are more effective than traditional critical path methods in the planning and scheduling of repetitive construction projects. Nevertheless, almost all the repetitive scheduling methods developed so far have been based on the premise that a repetitive project is comprised of many identical production units. In this research a non-unit-based algorithm for the planning and scheduling of repetitive projects is developed. Instead of repetitive production units, repetitive or similar activity groups are identified and employed for scheduling. The algorithm takes into consideration: (1) the logical relationship of activity groups in a repetitive project; (2) the usage of various resource crews in an activity group; (3) the maintaining of resource continuity; and (4) the time and cost for the routing of resource crews. A sample case study and a case study of a sewer system project are conducted to validate the algorithm, as well as to demonstrate its application. Results and findings are reported.

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CE Database subject headings: Construction industry; Project management; Scheduling; Algorithms; Resource management.

Introduction

Repetitive scheduling methods are more effective than traditional critical path methods (CPM) in modeling and planning repetitive activities. They address the need to maintain work continuity and uninterrupted resource deployment during the construction of this repetitive type of project. As a result they are more suitable for the scheduling and resource planning of repetitive construction projects.

Nonetheless, most repetitive scheduling methods developed so far have been based on the premise that a repetitive project consists of many identical production units. A unit network is employed to represent the production activities, as well as their sequence within one production unit. The unit network is then repeated for each of the production units, as shown in Fig. 1. Normally a crew is assigned to each activity in the unit network. In an ideal situation, the crew will perform the same activity consecutively and continuously in different production units.

In practice, however, the production units in many repetitive projects may not be identical. For instance, in a piling project, the excavation depth and the soil conditions encountered when placing each pile will not be exactly the same. In a pipeline-laying project, the number of manholes and the number of pipe sections would not normally be the same, which makes the identification of repetitive production units a bit tricky. Also, different construction methods may require different types of equipment and different crews, so that time required for laying pipe varies for different sections. In a multihousing project, the interior design of each house may be different, therefore the required workload, as well as the time duration and cost, will differ. Moreover, even in a typical repetitive project with many identical production units, more often it contains portions of work with a nonrepetitive nature.

A non-unit-based algorithm for planning and scheduling repetitive projects is developed. Instead of repetitive production units, repetitive or similar activity groups are identified and employed for the scheduling process. The developed algorithm, as well as its rationale, is described in the paper. A sample case and a case study of a sewer system construction project are conducted

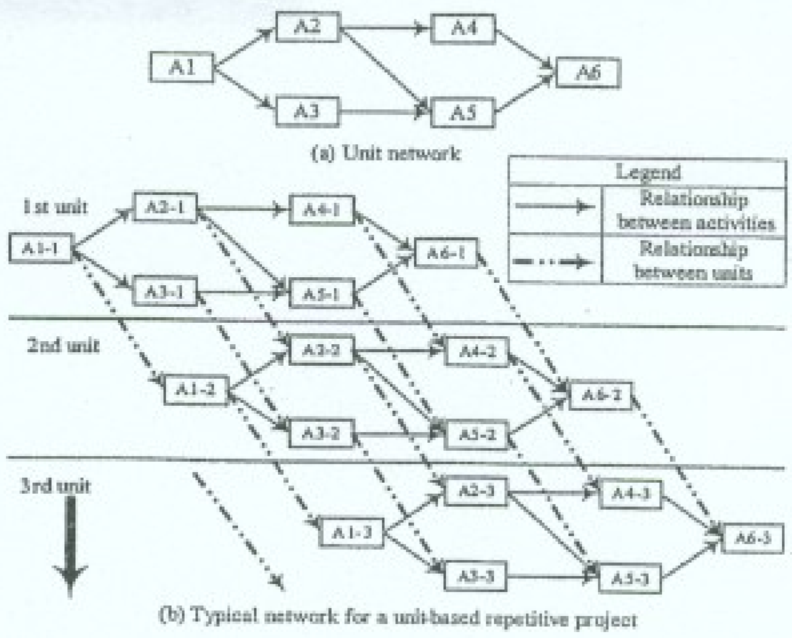

Fig. 1. Network sequence for typical unit-based repetitive project

[1]Associate Professor, Institute of Construction Engineering and Management, National Central Univ., No. 300, Jhongda Rd., Jhongli City, Taoyuan 32001, Taiwan (R.O.C.) (corresponding author). E-mail: rhuang@cc.ncu.edu.tw

[2]Associate Professor, Dept. of Air Transportation, Kainan Univ., No. 1, Kainan Rd., Luchu, Taoyuan 338, Taiwan (R.O.C.). E-mail: kssun@mail.knu.edu.tw

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Table 1. Review of Previous Work

Author(s)	Method	Unit based	Fixed work sequence	Non-typical activity	Multiple resource assignment	Resource continuity
Carr and Meyer (1974)	LOB (Line-of-balance method)	Yes	Yes	No	No	Yes
O'Brien (1975)	VPM (Vertical production method)	Yes	Yes	No	No	Yes
Selinger (1980)	Const. planning	Yes	Yes	Yes	No	Yes
Johnston (1981)	LSM (Linear scheduling method)	Yes	Yes	Yes	No	Suggested
Stradal and Cacha (1982)	Time space scheduling	Yes	Yes	Yes	No	Suggested
Arditi and Albulak (1986)	LOB	Yes	Yes	No	No	Yes
Chrzanowski and Johnston (1986)	LSM	Yes	Yes	Yes	No	Yes
Reda (1990)	RPM (Repetitive project modeling)	Yes	Yes	No	No	Yes
El-Rays and Moselhi (1998)	Resource-driven scheduling	Yes	No	Yes	No	No
Hamelink and Rowings (1998)	Linear scheduling model	Yes	Yes	No	No	Yes
Harris and Ioannou (1998)	RSM (Repetitive scheduling method)	Yes	Yes	Yes	No	No
Hegazy and Wassef (2001)	Repetitive non-serial activity scheduling	Yes	Yes	No	No	No

for demonstration and validation. Results and findings are reported.

Literature Review

Traditional network scheduling methods, such as CPM, program evaluation review technique (PERT), and bar charting are generally considered as less effective for the planning of repetitive construction projects, due to their inability to maintain resource work continuity in scheduling. Many linear, or repetitive, scheduling methods, as shown in Table 1, have been developed, with each of them featuring unique functions and/or applications.

The idea of repetitive scheduling originated from the manufacturing industry, with the use of mass production line units. These production line units are identical. The manufacturing process consists of a series of workstations requiring the same resources (e.g., equipment, laborer, etc.) for processing. Resources are normally stationed on the plant floor during the production process with no movement of resource considered necessary. A typical repetitive scheduling method is the line-of-balance method (LOB) (Carr and Mayer 1974; O'Brien 1975; Arditi and Albulak 1986; Reda 1990; Hegazy and Wassef 2001), which provides a simple method for scheduling and controlling the production progress. However, its modeling and application to construction projects requires the simplification of repetitive activities to have a single duration, the same resource usage, and in a fixed production order. This somewhat limits the applicability of the LOB method, especially in more diversified and complex repetitive construction projects.

Subsequent construction repetitive scheduling methods (Selinger 1980; Johnston 1981; Chrzanowski and Johnston 1986; El-Rayes and Moselhi 1998; Harris and Ioannou 1998) have tried to release the single duration constraint for repetitive activities. Production units need not be identical, but merely similar. El-Rayes and Moselhi (1998) for example, designated operations by a work group with the same duration as a "typical repetitive

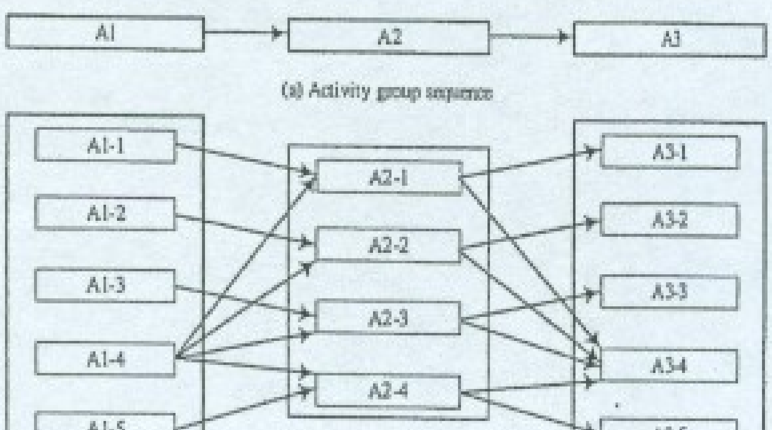


Fig. 2. Illustration of non-unit-based repetitive project

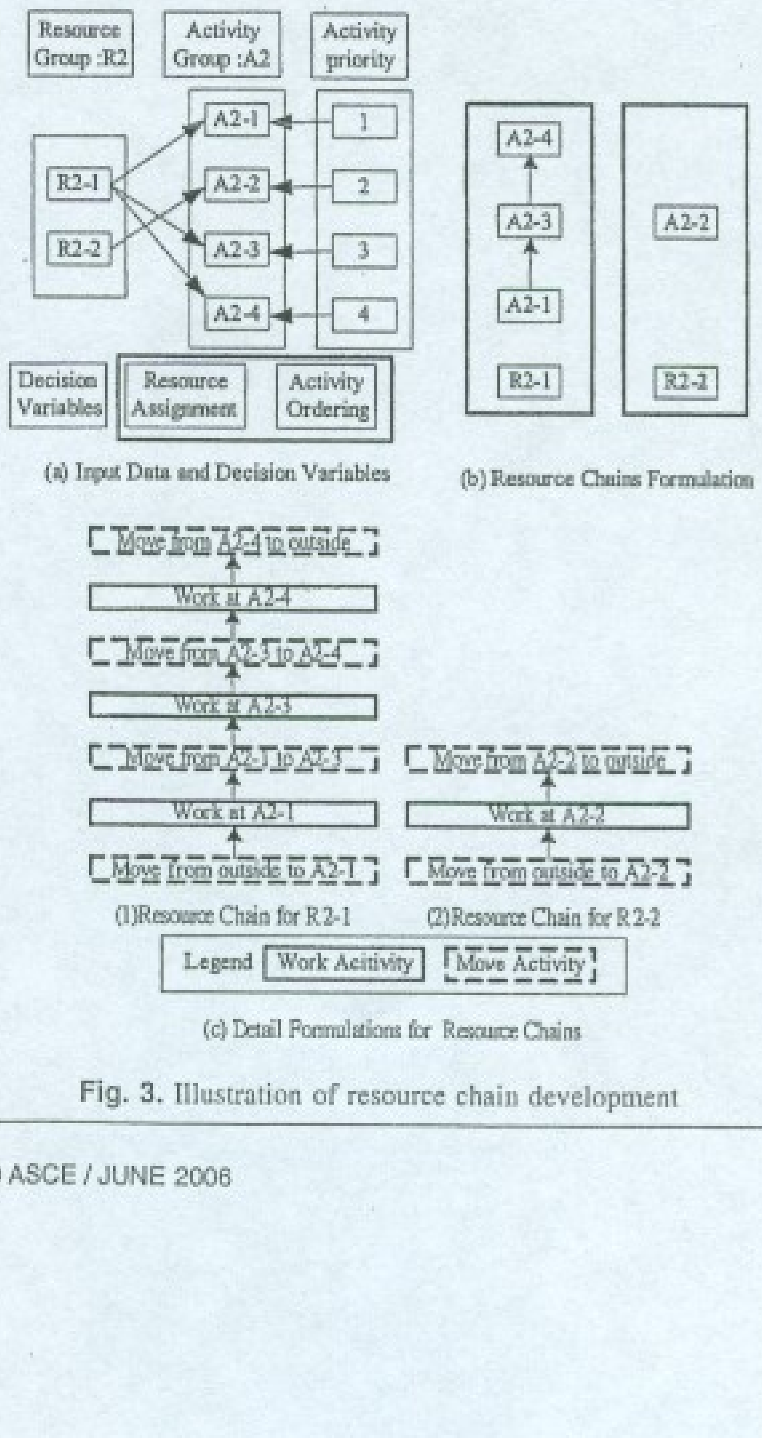
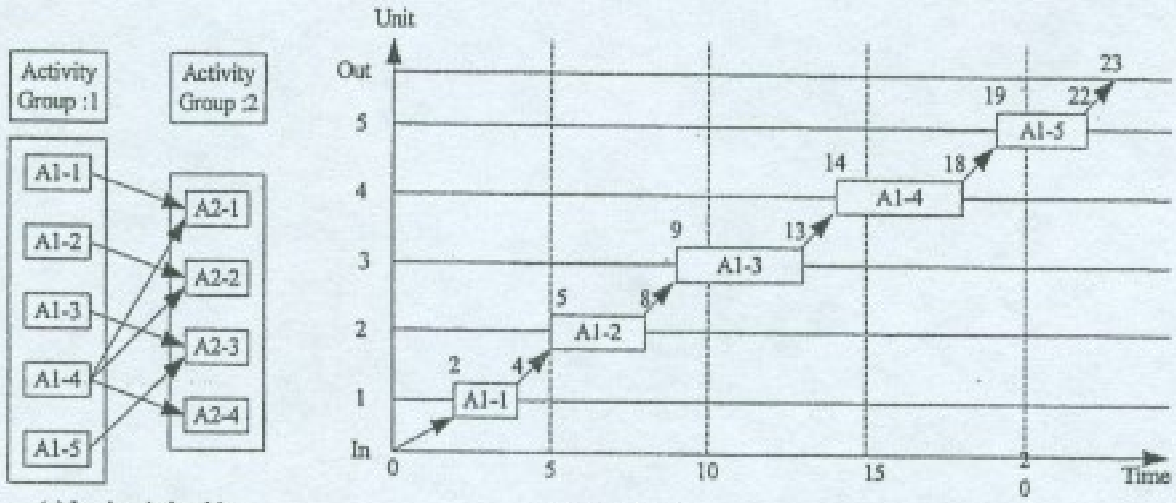


Fig. 3. Illustration of resource chain development

Table 2. Work Sheet for Positioning Resource Chain R2-1

Activity	Duration	Baseline Schedule		Preceding activity	Last finishing time for preceding act.	Earliest starting time for R2-1	Project schedule	
		Start	Finish				Start	Finish
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
In→A2-1	2	0	2				17	19
A2-1	2	2	4	A1-1; A1-4	Max(4,18)=18	18-2=16	19	21
A2-1→A2-3	1	4	5				21	22
A2-3	4	5	9	A1-3; A1-5	Max(13,22)=22	22-5=17(Max)	22	26
A2-3→A2-4	1	9	10				26	27
A2-4	3	10	13	A1-4	18	18-10=8	27	30
A2-4→Out	2	13	15				30	32



(a) Logic relationship between workgroups

(b) Project schedule for resource chain preceding R2-1

Fig. 4. Preceding resource chain for R2-1

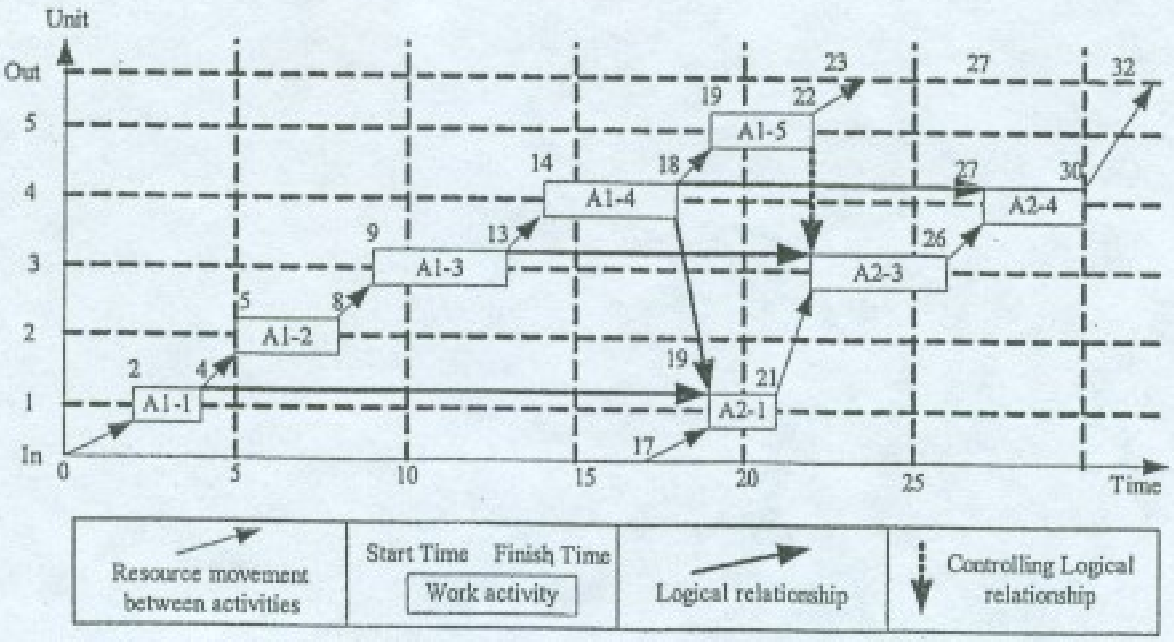


Fig. 5. Scheduling result for resource chain R2-1

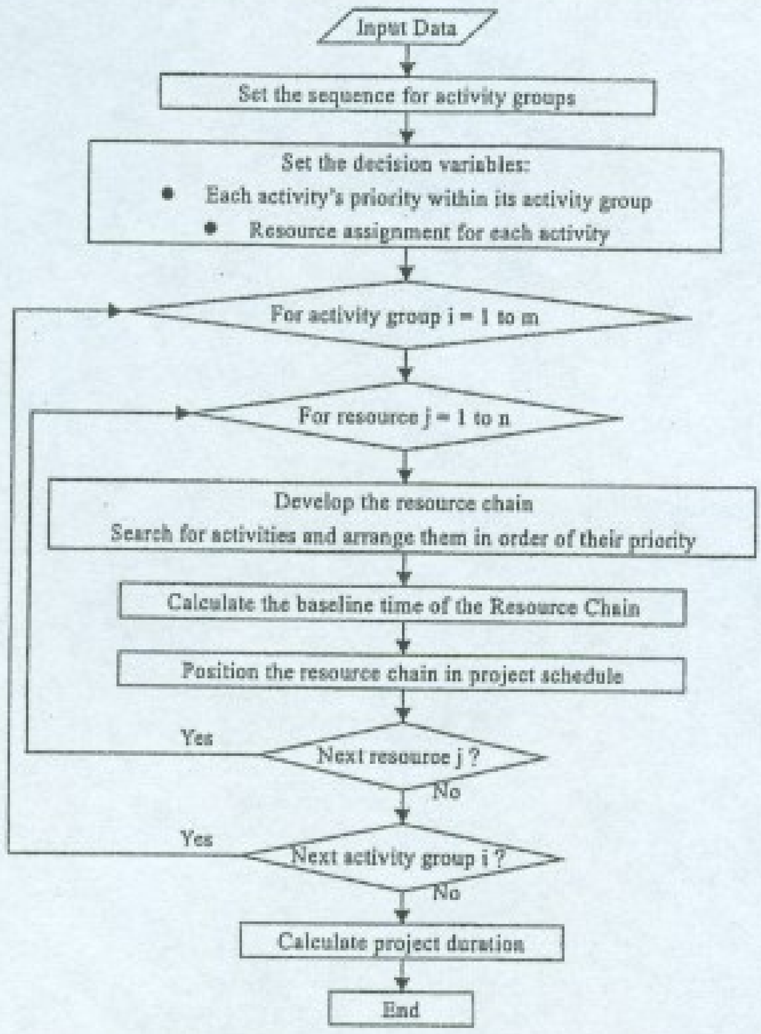


Fig. 6. Procedure steps for developed algorithm

activity" and one with a different duration as a "nontypical repetitive activity." They also pointed out that the "nontypical repetitive activity" is common in repetitive projects; thus it is inadequate to treat repetitive operations within one work group as the same, the difference between each work item should be considered during preconstruction planning.

Nonetheless, all these methods are still based on the premise that a repetitive project involves repeated processing units. Given this traditional definition of a repetitive project, the relationship between activities is constrained to being unitized (Fig. 1). The same sequential order of the different production units, as well as same resource usage, holds for each repeated activity. In the real world, however, multiple resource crews using different construction methods, combinations of equipment and types of labor, depending on availability, may perform repetitive activities. In addition, the duration and cost for mobilizing resource crews in and out of the job site, as well as the routing between production units, are not considered in the traditional repetitive methods. It becomes essential to take these into account if multiple resource usage for repetitive activities is allowed.

Table 3. Activity Group Data for Sample Case Study

Activity group	Number of activities	Pregroup	Maximum number of available resource crews	Resource code
A1	5	—	1	R1-1
A2	4	1	2	R2-1-R2-2
A3	5	2	1	R3-1

Table 4. Duration for Activity and Resource Movement in Sample Case (Units: Days)

	To activity					
From activity →	Out	1-1	1-2	1-3	1-4	1-5
	(a) Resource R1-1					
In	—	1	1	1	1	1
1-1	1	2	1	1	1	1
1-2	1	1	2	1	1	1
1-3	1	1	1	2	1	1
1-4	1	1	1	1	2	1
1-5	1	1	1	1	1	2
	To activity					
From activity →	Out	2-1	2-2	2-3	2-4	
	(b) Resource R2-1					
In	—	1	1	1	1	
2-1	1	6	1	1	1	
2-2	1	1	6	1	1	
2-3	1	1	1	6	1	
2-4	1	1	1	1	6	
	To activity					
From activity →	Out	2-1	2-2	2-3	2-4	
	(c) Resource R2-2					
In	—	1	1	1	1	
2-1	1	6	1	1	1	
2-2	1	1	6	1	1	
2-3	1	1	1	6	1	
2-4	1	1	1	1	6	
	To activity					
From activity →	Out	3-1	3-2	3-3	3-4	3-5
	(d) Resource R3-1					
In	—	1	1	1	1	1
3-1	1	2	1	1	1	1
3-2	1	1	2	1	1	1
3-3	1	1	1	2	1	1
3-4	1	1	1	1	2	1
3-5	1	1	1	1	1	2

"Non-Unit-Based" Repetitive Projects

The traditional view of a repetitive project is that such a project repeats in production units. However, a non-unit-based repetitive project takes the view that the project repeats in activities! As shown in Fig. 2, activity groups in a repetitive project are identified. Each activity group contains activities having the same functional purpose, but with different resource usage, construction conditions, time, costs, and so on. The logical relationships between activity groups, as well as between the individual activities in different activity groups are defined. There is no "hard logic" constraint for related activities within the same activity group. In bridge construction, for instance, foundation, pier, and deck activity groups are identified, with each group contains the same activities for different spans. For each span, the foundation has to be built before the pier and the pier has to be built before the deck, but within an activity group, says, for the foundation, there is no particular order among the activities (spans).

Table 5. Input Data for Three Sample Scenarios

Activity	Scenario 1 Operating priority	Scenario 1 Assigned resource	Scenario 2 Operating priority	Scenario 2 Assigned resource	Scenario 3 Operating priority	Scenario 3 Assigned resource
A1-1	1	R1-1	2	R1-1	2	R1-1
A1-2	2	R1-1	3	R1-1	3	R1-1
A1-3	3	R1-1	4	R1-1	4	R1-1
A1-4	4	R1-1	1	R1-1	1	R1-1
A1-5	5	R1-1	5	R1-1	5	R1-1
A2-1	1	R2-1	1	R2-1	1	R2-1
A2-2	2	R2-1	2	R2-1	2	R2-2
A2-3	3	R2-1	3	R2-1	3	R2-1
A2-4	4	R2-1	4	R2-1	4	R2-2
A3-1	1	R3-1	1	R3-1	1	R3-1
A3-2	2	R3-1	2	R3-1	2	R3-1
A3-3	3	R3-1	3	R3-1	3	R3-1
A3-4	4	R3-1	4	R3-1	5	R3-1
A3-5	5	R3-1	5	R3-1	4	R3-1

A non-unit-based repetitive project has the following characteristics:

1. The activities in an activity group are similar, but not identical. Individual activities in an activity group share a common functional purpose, but each of them may vary in duration, resource usage, and cost.
2. The logical work relationships are more generalized. In traditional repetitive scheduling methods, every activity in a unit network follows the same production order. For instance, in Fig. 1 the work order of activity *A* is to work first on production unit 1, then unit 2, then 3, and so on. The rest of the activities in the unit network also share the same order. However, in the non-unit-based repetitive scheduling, activities are no longer bounded by the above constraints but are more generalized, which is closer to real world practices.
3. There is no "hard logic" relationship between activities in the same activity group. By assigning a different work order for activities in an activity group, scheduling and project cost will be different as a result. However, the best order whereby an optimized schedule and/or cost may be obtained is not intuitional. In non-unit-based repetitive scheduling, no hard working order is assigned to the activities in an activity group. It becomes a decision variable determined by the planner or decision maker.
4. Multiple working crews can be employed in an activity group. In most traditional repetitive scheduling methods, only a single crew performs activities in an activity group. Traditional methods do not take into account that in the real world multiple crews, with the same or different equipments, laborers, as well as construction methods, may be employed in an activity group, depending on the project demands and the availability of resource crews. Different types of resource

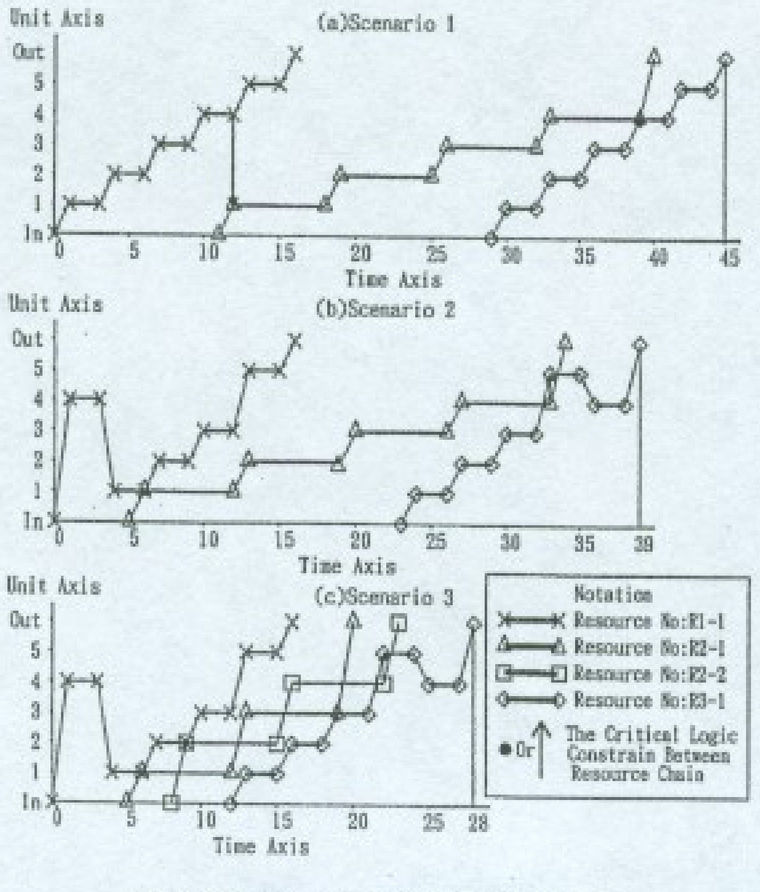


Fig. 7. Scheduling results of sample case

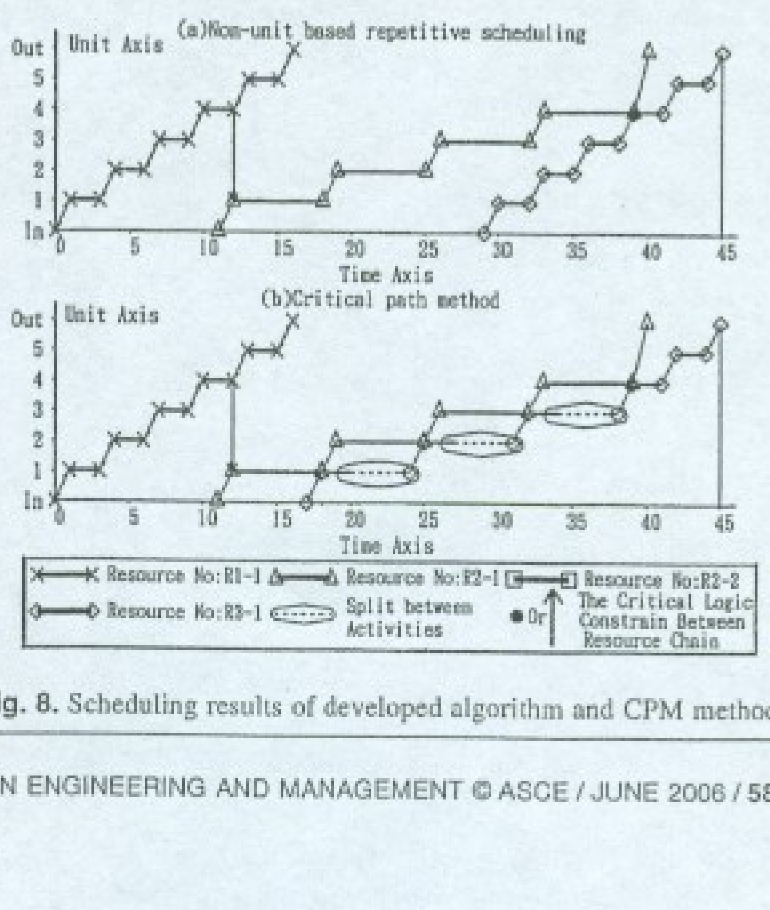


Fig. 8. Scheduling results of developed algorithm and CPM methods

國立雲林科技大學
95學年度博士班招生入學考試試題
所別：工程科技研究所
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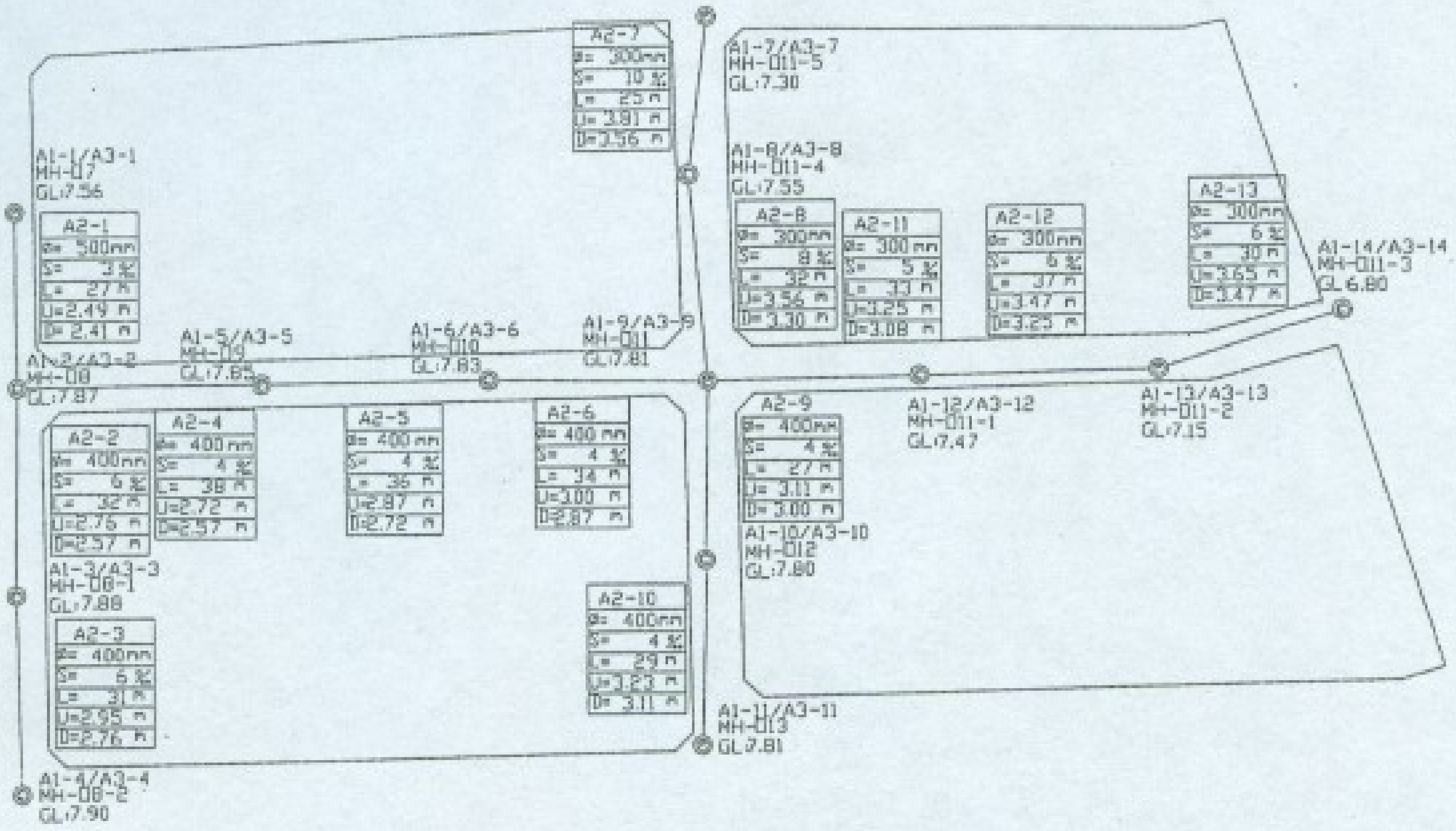

Fig. 9. System layout of sewer project

usage will have impact on activity scheduling, as well as the project duration and cost.

5. Cost and time for the routing of various resource crews among activities in an activity group are considered. The mobilization, demobilization, and routing of the various resource crews on a job site inevitably influences time and cost. Since non-unit-based repetitive scheduling allows for the using of multiple resource crews in activity group, and there is no "hard logic" constraint on activity relations, it becomes essential to take into account the incurred time and cost for mobilizing, demobilizing, and routing the resource crews.

Development of Non-Unit-Based Scheduling Algorithm

A non-unit-based scheduling algorithm is developed in this study, with the following objectives and/or principals:

1. To comply with the logical relationship between activity groups in a repetitive project;
2. To allow for the usage of multiple resource crews in an activity group;
3. To maintain the continuity for resource usage; and
4. To consider the time and cost for routing the various resource crews in a job.

There are three main steps in the developed algorithm. They are described respectively below.

Step 1. Identify Activity Groups as Well as Their Sequential Relationships

Activities in a repetitive project are grouped into activity groups according to functionality. It is possible that some activity groups will include more activities than others. For nonrepetitive activities, it is also possible to designate a separate activity group for

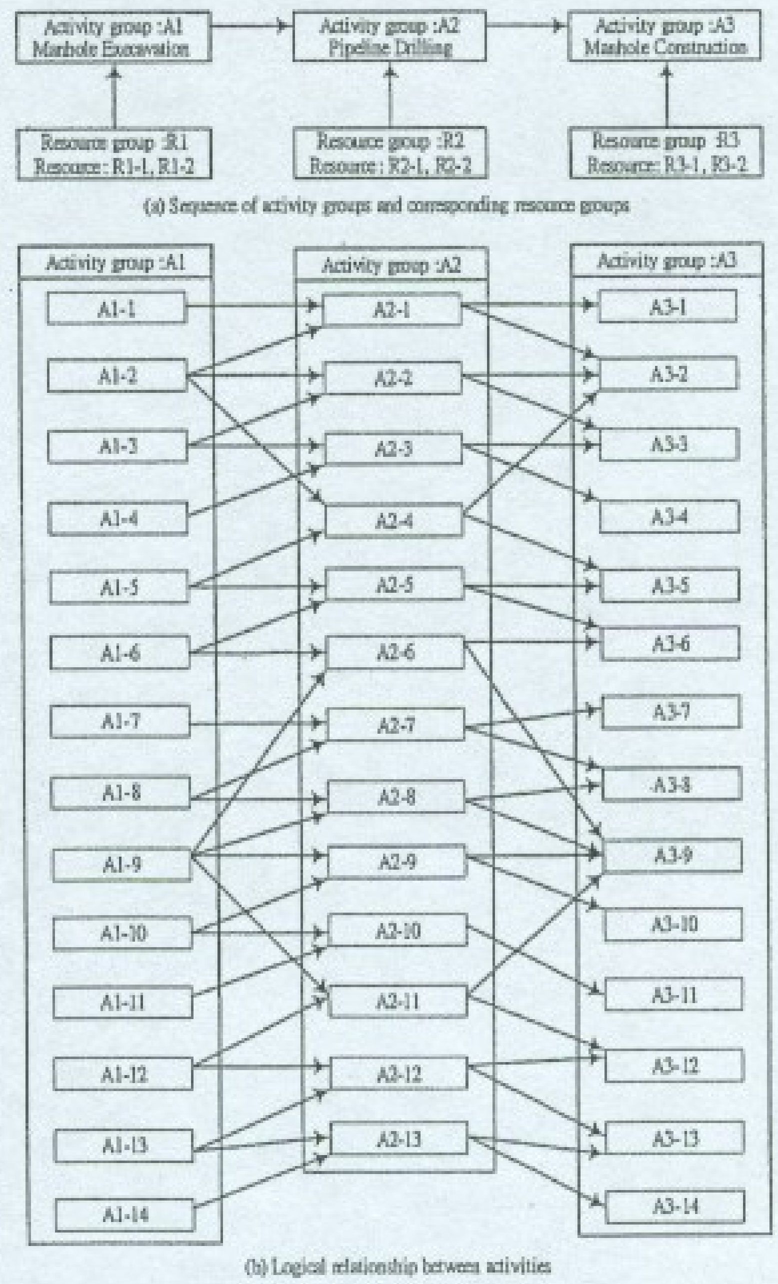

Fig. 10. Relationship between activities in sewer system project

Table 6. Main Equipment Used by Workgroups for Construction of Sewer System

Workgroup	Main construction equipment
A1 Manhole excavation	1. Casing machine
	2. Excavator
	3. Earth hauling truck
	4. Grouting machine
	5. Other assistant facilities
A2 Pipeline drilling	1. HDD machine (earth pressure balanced type of slurry pressure type)
	2. Other assistant facilities
A3 Manhole construction	1. Mobil crane
	2. Other assistant facilities

each of them. In addition, a network describing the sequential relationships of these activity groups is created. Fig. 2(a) shows an example.

Step 2. Development of Resource Chains

Since multiple resource crews can be employed for activity operations; each activity group will have an associated resource group. As shown in Fig. 3(a), activity group 2 is associated with resource group 2. There are two resource types, R2-1 and R2-2, which are available for activity group 2 operations. Once the scheduler decides on the decision variables for resource assignment and activity priority, resource chains for each type can be determined. In Fig. 3(a), for instance, resource type R2-1 is assigned for work on activities A2-1, A2-3, and A2-4, while resource type R2-2 is only used for activity A2-2. In addition, the operational priority for activity group 2 is A2-1, A2-2, A2-3, and then A2-4. Thus, as shown in Fig. 3(b), R2-1 will first perform A2-1, then A2-3, and finally A2-4, while R2-2 will perform only A2-2. A more detailed formulation of the resource chains, R2-1 and R2-2, taking into account resource mobilization and movement can then be developed, as shown in Fig. 3(c). The R2-1 resource chain, for instance, has the following working sequence; R2-1 is mobilized from outside for activity A2-1, works on A2-1, is relocated to A2-3, works on A2-3, is again relocated to A2-4, works on A2-4, and finally is demobilized out of the job site. It is

Table 8. Duration of Mobilization/Demobilization of Work Crews in Sewer System Case (Units: Days)

Resource code	Mobilization	Demobilization
R1-1	1	0.5
R1-2	0.5	0.5
R2-1	3	1
R2-2	1.5	1
R3-1	0.5	0.5
R3-2	0.5	0.5

noted that alternative settings for the resource assignment and activity priority decision variables will result in different resource chain schedules.

Step 3. Position Resource Chains for Project Scheduling

After the formulation of resource chains in each activity group, one may follow the activity group scheduling sequence in Step 1, and apply the following substeps for the scheduling of each resource chain:

1. Calculate the baseline schedule: By setting the time for a resource to enter the project site to Day 0, the starting and finishing time of each action in the resource chain can be calculated. For instance, Table 2 shows the work sheet for positioning the R2-1 resource chain in Fig. 3. Column 1 lists all the actions for resource chain R2-1, and column 2 lists their respective duration. By setting the day for the mobilization of R2-1 at the jobsite as Day 0, a baseline starting and finishing time schedule for the actions in resource chain R2-1 can be calculated, which is shown in columns 3 and 4 of Table 2.
2. Calculate the earliest possible starting time for each activity: On the basis at the latest finishing time of the preceding activities, the earliest possible starting time of each activity in the resource chain can be determined. Following the example of resource chain R2-1, in Fig. 4(a) we see the logical relation between activities in activity groups 1 and 2. The activities preceding A2-1, A2-3, and A2-4 are, respectively,

Table 7. Activity Duration in Sewer System Case (Units: Days)

Activity code	Duration R1-1	Duration R1-2	Activity code	Duration R2-1	Duration R2-2	Activity code	Duration R3-1	Duration R3-2
A-1	1.88	2.72	A2-1	7.71	6.75	A3-1	1.16	1.39
A-2	2.44	3.00	A2-2	9.14	8.00	A3-2	0.90	1.20
A-3	2.20	3.11	A2-3	7.75	6.89	A3-3	1.15	1.38
A-4	2.02	2.49	A2-4	10.86	9.50	A3-4	0.84	1.13
A-5	2.00	2.80	A2-5	10.29	9.00	A3-5	1.00	1.20
A-6	1.81	2.23	A2-6	8.50	7.56	A3-6	0.72	0.95
A-7	1.76	2.17	A2-7	6.25	5.56	A3-7	0.68	0.91
A-8	1.49	2.13	A2-8	9.14	8.00	A3-8	0.87	1.04
A-9	2.21	3.11	A2-9	7.71	6.75	A3-9	1.16	1.39
A-10	2.02	2.49	A2-10	7.25	6.44	A3-10	0.85	1.13
A-11	2.80	3.80	A2-11	8.25	7.73	A3-11	1.10	1.32
A-12	1.51	2.16	A2-12	9.25	8.22	A3-12	0.88	1.06
A-13	1.96	2.42	A2-13	10.00	8.57	A3-13	0.81	1.08
A-14	1.75	2.53	—	—	—	A3-14	1.06	1.28

Table 9. Duration of Movement of Resource Crew R1-1 between Activities in Sewer System Case (Units: Days)

	To activity													
From activity →	A1-1	A1-2	A1-3	A1-4	A1-5	A1-6	A1-7	A1-8	A1-9	A1-10	A1-11	A1-12	A1-13	A1-14
A1-1	—	0.02	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.11	0.11	0.11	0.11	0.11
A1-2	0.02	—	0.02	0.04	0.02	0.05	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
A1-3	0.08	0.02	—	0.02	0.08	0.08	0.11	0.11	0.08	0.11	0.08	0.11	0.11	0.11
A1-4	0.08	0.04	0.02	—	0.08	0.08	0.11	0.11	0.08	0.08	0.08	0.11	0.11	0.11
A1-5	0.08	0.02	0.08	0.08	—	0.02	0.08	0.08	0.04	0.08	0.08	0.08	0.08	0.08
A1-6	0.08	0.05	0.08	0.08	0.02	—	0.08	0.08	0.02	0.08	0.08	0.08	0.08	0.08
A1-7	0.08	0.08	0.11	0.11	0.08	0.08	—	0.02	0.04	0.08	0.08	0.08	0.08	0.08
A1-8	0.08	0.08	0.11	0.11	0.08	0.08	0.02	—	0.02	0.08	0.08	0.08	0.08	0.08
A1-9	0.08	0.08	0.08	0.08	0.04	0.02	0.04	0.02	—	0.02	0.04	0.02	0.04	0.06
A1-10	0.11	0.08	0.11	0.08	0.08	0.08	0.08	0.08	0.02	—	0.08	0.08	0.08	0.08
A1-11	0.11	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.04	0.08	—	0.08	0.08	0.08
A1-12	0.11	0.08	0.11	0.11	0.08	0.08	0.08	0.08	0.02	0.08	0.08	—	0.02	0.04
A1-13	0.11	0.08	0.11	0.11	0.08	0.08	0.08	0.08	0.04	0.08	0.08	0.02	—	0.02
A1-14	0.11	0.08	0.11	0.11	0.08	0.08	0.08	0.08	0.06	0.08	0.08	0.04	0.02	

identified and listed in column 5 of Table 2. In addition, Fig. 4(b) shows the scheduling of the resource chains for the preceding activity group 1. In this case, only one resource crew is employed to perform activities in activity group 1, therefore, there is only one resource chain developed for activity group 1. The last finishing time of the preceding activities for A2-1, A2-3, and A2-4 is calculated from Fig. 4(b), and is shown in column 6 of Table 2. The latest finishing time of the preceding activities is also the earliest starting time of the next activity.

3. Determine the earliest possible starting time for a resource chain: By subtracting the starting time of an activity on the baseline schedule from the earliest starting time obtained from substep 2, the earliest possible starting time for the resource chain R2-1 can be calculated and determined. For example, for resource chain R2-1, the earliest possible starting time for activity A2-3 is on the 22nd day (column 6 of Table 2). Given the baseline schedule, the starting time of activity A2-3 will be on the 5th day (column 3). Therefore, the earliest possible starting time for resource chain R2-1 is on the 17th day (22-5), based on the constraints for activity A2-3. In a similar fashion, the earliest possible starting time for resource chain R2-1 can also be calculated based on the constraints for activities A2-1 and A2-4, that is the 16th and the 8th day, respectively. Thus, the 17th day (a maximum of 17, 16, and 8) is dominant and becomes the earliest possible starting time for resource chain R2-1. Meanwhile, since the 17th day was originally governed by activity A1-5, a controlling logical relationship is formed between activities A1-5 and A2-3, which in turn establishes a critical logical constraint between the two resource chains (Fig. 5).
4. Calculate the project schedule for the resource chain: After the earliest possible starting time for a resource chain is determined from substep 3, the starting and finishing time for each work actions in the resource chain can now be calculated, in accordance with their durations. For example, again using resource chain R2-1, the calculation results in columns 8 and 9 of Table 2 can be obtained. Fig. 5 depicts the scheduling result.
5. Repeat substeps 1–4 for each resource chain in the project, following the sequential order of the activity groups.

Table 10. Duration of Movement of Resource Crew R1-2 between Activities in Sewer System Case (Units: Days)

	To activity													
From activity →	A1-1	A1-2	A1-3	A1-4	A1-5	A1-6	A1-7	A1-8	A1-9	A1-10	A1-11	A1-12	A1-13	A1-14
A1-1	—	0.02	0.10	0.10	0.10	0.10	0.11	0.11	0.11	0.13	0.13	0.13	0.13	0.13
A1-2	0.02	—	0.03	0.05	0.03	0.06	0.11	0.11	0.10	0.11	0.11	0.11	0.11	0.11
A1-3	0.10	0.03	—	0.03	0.10	0.10	0.13	0.13	0.11	0.13	0.11	0.13	0.13	0.13
A1-4	0.10	0.05	0.03	—	0.10	0.11	0.13	0.13	0.11	0.11	0.10	0.13	0.13	0.13
A1-5	0.10	0.03	0.10	0.10	—	0.03	0.10	0.10	0.06	0.10	0.10	0.10	0.11	0.11
A1-6	0.10	0.06	0.10	0.11	0.03	—	0.10	0.10	0.03	0.10	0.10	0.10	0.10	0.11
A1-7	0.11	0.11	0.13	0.13	0.10	0.10	—	0.02	0.05	0.10	0.10	0.10	0.10	0.11
A1-8	0.11	0.11	0.13	0.13	0.10	0.10	0.02	—	0.03	0.10	0.10	0.10	0.10	0.10
A1-9	0.11	0.10	0.11	0.11	0.06	0.03	0.05	0.03	—	0.02	0.05	0.03	0.06	0.08
A1-10	0.13	0.11	0.13	0.11	0.10	0.10	0.10	0.10	0.02	—	0.10	0.10	0.10	0.10
A1-11	0.13	0.11	0.11	0.10	0.10	0.10	0.10	0.10	0.05	0.10	—	0.10	0.10	0.11
A1-12	0.13	0.11	0.13	0.13	0.10	0.10	0.10	0.10	0.03	0.10	0.10	—	0.03	0.06
A1-13	0.13	0.11	0.13	0.13	0.11	0.10	0.10	0.10	0.06	0.10	0.10	0.03	—	0.03
A1-14	0.13	0.11	0.13	0.13	0.11	0.11	0.11	0.10	0.08	0.10	0.11	0.06	0.03	—

Table 11. Duration of Movement of Resource Crew R2-1 between Activities in Sewer System Case (Units: Days)

	To activity												
From activity →	A2-1	A2-2	A2-3	A2-4	A2-5	A2-6	A2-7	A2-8	A2-9	A2-10	A2-11	A2-12	A2-13
A2-1	—	1.06	1.06	1.06	1.06	1.11	1.11	1.11	1.13	1.16	1.11	1.17	1.17
A2-2	1.06	—	0.00	1.06	1.06	1.11	1.16	1.11	1.11	1.11	1.11	1.17	1.17
A2-3	1.06	0.00	—	1.06	1.06	1.11	1.16	1.11	1.11	1.11	1.11	1.17	1.17
A2-4	1.06	1.06	1.06	—	0.00	1.04	1.10	1.04	1.04	1.10	1.04	1.11	1.11
A2-5	1.06	1.06	1.06	0.00	—	1.04	1.10	1.04	1.04	1.10	1.04	1.11	1.11
A2-6	1.11	1.11	1.11	1.04	1.04	—	1.04	0.00	0.00	1.04	0.00	1.04	1.04
A2-7	1.11	1.16	1.16	1.10	1.10	1.07	—	1.04	1.04	1.09	1.04	1.10	1.10
A2-8	1.11	1.11	1.11	1.04	1.04	0.00	1.04	—	0.00	1.04	0.00	1.04	1.04
A2-9	1.13	1.11	1.11	1.04	1.04	0.00	1.04	0.00	—	1.04	0.00	1.04	1.04
A2-10	1.16	1.11	1.11	1.10	1.10	1.04	1.09	1.04	1.04	—	1.04	1.10	1.10
A2-11	1.11	1.11	1.11	1.04	1.04	0.00	1.04	0.00	0.00	1.04	—	1.04	1.04
A2-12	1.17	1.17	1.17	1.11	1.11	1.04	1.10	1.04	1.04	1.10	1.04	—	0.00
A2-13	1.17	1.17	1.17	1.11	1.11	1.04	1.10	1.04	1.04	1.10	1.04	0.00	—

Fig. 6 shows a flow-chart that summarizes the computational steps of the developed scheduling algorithm.

Sample Case Study

A sample case, consisting of three work groups and 14 activities, is employed to demonstrate and validate the developed algorithm. The contents of the activity groups and their logical relationships are shown in Fig. 2. Table 3 lists the associated number of resource crews employed for each activity group. Resource crews R2-1 and R2-2, for instance, are employed to work on the activities in activity group 2.

Since the duration for the movement of resource crews is considered in the developed algorithm, it is necessary to enter the corresponding durational data. Table 4 lists activity duration, as well as the duration for resource movement, for the sample case. It is noted that in the table, the time from activity x to the same activity x means the duration for activity x. For instance, the time "from activity A1-2" "to activity A1-2" is 2 days, which represents the duration of activity A1-2.

Three sample scenarios, as listed below, are tested. Table 5 shows their respective data input.

1. Only one resource type is used for each work group. In this case, only R2-1 is employed in activity group 2.
2. The operating priority of activity A1-4 becomes the highest, and that of activity A3-4 the lowest. The rest of the input data are the same as those used in Scenario 1.
3. One more resource, R2-2, is employed for the activity group 2 operations. The rest of the input data are the same as those used in Scenario 2.

The scheduling results for the three scenarios are shown in Fig. 7. Each line in the figure represents the timing of a resource chain, from entering to exiting the project site. The flat segments in the line represent the elapsed time durations of activities, while the sloped segments depict the movement of resources between activities, or in or out of the project site. It can be seen from the figure that all resources maintain their work continuity. The total project duration results for Scenarios 1, 2, and 3 are 45, 39, and 28 days, respectively.

In Scenario 1, since A1-4 is the activity preceding all activities in activity group 2 (Fig. 2), it means that activity group 2 cannot start until A1-4 is finished. Also, since all activities in activity group 2 precede the A3-4 activity, A3-4 cannot commence until activity group 2 is finished. As a result, the starting time of the

Table 12. Duration of Movement of Resource Crew R2-2 between Activities in Sewer System Case (Units: Days)

	To activity												
From activity →	A2-1	A2-2	A2-3	A2-4	A2-5	A2-6	A2-7	A2-8	A2-9	A2-10	A2-11	A2-12	A2-13
A2-1	—	1.55	1.55	1.55	1.55	1.59	1.59	1.59	1.61	1.64	1.59	1.64	1.64
A2-2	1.55	—	0.00	1.56	1.56	1.59	1.64	1.59	1.59	1.59	1.59	1.65	1.65
A2-3	1.55	0.00	—	1.56	1.56	1.59	1.64	1.59	1.59	1.59	1.59	1.65	1.65
A2-4	1.55	1.56	1.56	—	0.00	1.54	1.58	1.54	1.54	1.58	1.54	1.59	1.59
A2-5	1.55	1.56	1.56	0.00	—	1.54	1.58	1.54	1.54	1.58	1.54	1.59	1.59
A2-6	1.59	1.59	1.59	1.54	1.54	—	1.53	0.00	0.00	1.53	0.00	1.54	1.54
A2-7	1.59	1.64	1.64	1.58	1.58	1.53	—	1.53	1.53	1.58	1.53	1.58	1.58
A2-8	1.59	1.59	1.59	1.54	1.54	0.00	1.53	—	0.00	1.53	0.00	1.54	1.54
A2-9	1.61	1.59	1.59	1.54	1.54	0.00	1.53	0.00	—	1.53	0.00	1.54	1.54
A2-10	1.64	1.59	1.59	1.58	1.58	1.53	1.58	1.53	1.53	—	1.53	1.58	1.58
A2-11	1.59	1.59	1.59	1.54	1.54	0.00	1.53	0.00	0.00	1.53	—	1.54	1.54
A2-12	1.64	1.65	1.65	1.59	1.59	1.54	1.58	1.54	1.54	1.58	1.54	—	0.00
A2-13	1.64	1.65	1.65	1.59	1.59	1.54	1.58	1.54	1.54	1.58	1.54	0.00	—

Table 13. Duration of Movement of Resource Crew R3-1 between Activities in Sewer System Case (Units: Days)

	To activity													
From activity →	A3-1	A3-2	A3-3	A3-4	A3-5	A3-6	A3-7	A3-8	A3-9	A3-10	A3-11	A3-12	A3-13	A3-14
A3-1	—	0.00	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.04	0.04	0.04	0.04	0.04
A3-2	0.00	—	0.00	0.00	0.00	0.00	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
A3-3	0.02	0.00	—	0.00	0.02	0.02	0.04	0.04	0.02	0.04	0.02	0.04	0.04	0.04
A3-4	0.02	0.00	0.00	—	0.02	0.02	0.04	0.04	0.02	0.02	0.02	0.04	0.04	0.05
A3-5	0.02	0.00	0.02	0.02	—	0.00	0.02	0.02	0.00	0.02	0.02	0.02	0.02	0.02
A3-6	0.02	0.00	0.02	0.02	0.00	—	0.02	0.02	0.00	0.02	0.02	0.02	0.02	0.02
A3-7	0.02	0.02	0.04	0.04	0.02	0.02	—	0.00	0.00	0.02	0.02	0.02	0.02	0.02
A3-8	0.02	0.02	0.04	0.04	0.02	0.02	0.00	—	0.00	0.02	0.02	0.02	0.02	0.02
A3-9	0.02	0.02	0.02	0.02	0.00	0.00	0.00	0.00	—	0.00	0.00	0.00	0.00	0.00
A3-10	0.04	0.02	0.04	0.02	0.02	0.02	0.02	0.02	0.00	—	0.02	0.02	0.02	0.02
A3-11	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.00	0.02	—	0.02	0.02	0.02
A3-12	0.04	0.02	0.04	0.04	0.02	0.02	0.02	0.02	0.00	0.02	0.02	—	0.00	0.00
A3-13	0.04	0.02	0.04	0.04	0.02	0.02	0.02	0.02	0.00	0.02	0.02	0.00	—	0.00
A3-14	0.04	0.02	0.04	0.05	0.02	0.02	0.02	0.02	0.00	0.02	0.02	0.00	0.00	—

resource chain for activity group 3 is delayed. The total project duration of Scenario 1 is 45 days.

In Scenario 2, the operational priority of A1-4 is changed from the 4th to the 1st, thus the commencement of activity group 2 can be substantially earlier (6 days). In addition, in Scenario 2, the operational priority for A3-4 is lowered from 4th to 5th, so activity A3-5 can start before A3-4, but this has no impact on the total project duration. As a result, the total project duration is reduced to 39 days (45-6).

In Scenario 3, resource R2-2 is added to activity group 2. As shown in Fig. 7(c), resource chains R2-1 and R2-2 progress side by side. The time for processing activity group 2 is reduced from 29 days in Scenario 2 to 18 days in Scenario 3. Thus, the total project duration is reduced by 11 days (29–18) to 28 days.

The repetitive scheduling result of Scenario 1 is further compared with that of the traditional CPM for validation. Fig. 8 shows the scheduling results for both methods. The project durations in both methods are the same. But, since the scheme of "as early as possible" is applied in this case for CPM scheduling, the activities in workgroup 3, which performed by resource crew R3-1, are not executed in a continual fashion. In other words, resource crew R3-1 won't be able to maintain their work continuity and has to be in and out of the project site several times. A higher labor and equipment cost will likely incur as a result.

Case Study of Sewer System Construction Project

A sewer system construction project including 14 manholes and 13 pipeline segments is used to demonstrate the use of the developed algorithm. This construction project uses the pipe jacking method. The project work sequence consists of first excavating the two manholes connecting a pipeline segment, boring the pipeline segment, and then finishing manhole construction. The same sequence is then repeated for the construction of other manholes and pipeline segments. Three workgroups, namely the manhole excavation (A1), pipeline drilling (A2), and manhole construction (A3) workgroups, are distinguished by their roles in the project. Two activities (A1 and A3) are needed to complete

Table 14. Duration of Movement of Resource Crew R3-2 between Activities in Sewer System Case (Units: Days)

	To activity													
From activity →	A3-1	A3-2	A3-3	A3-4	A3-5	A3-6	A3-7	A3-8	A3-9	A3-10	A3-11	A3-12	A3-13	A3-14
A3-1	—	0.00	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.04	0.04	0.04	0.04	0.04
A3-2	0.00	—	0.00	0.00	0.00	0.00	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
A3-3	0.02	0.00	—	0.00	0.02	0.02	0.04	0.04	0.02	0.04	0.02	0.04	0.04	0.04
A3-4	0.02	0.00	0.00	—	0.02	0.02	0.04	0.04	0.02	0.02	0.02	0.04	0.04	0.04
A3-5	0.02	0.00	0.02	0.02	—	0.00	0.02	0.02	0.00	0.02	0.02	0.02	0.02	0.02
A3-6	0.02	0.00	0.02	0.02	0.00	—	0.02	0.02	0.00	0.02	0.02	0.02	0.02	0.02
A3-7	0.02	0.02	0.04	0.04	0.02	0.02	—	0.00	0.00	0.02	0.02	0.02	0.02	0.02
A3-8	0.02	0.02	0.04	0.04	0.02	0.02	0.00	—	0.00	0.02	0.02	0.02	0.02	0.02
A3-9	0.02	0.02	0.02	0.02	0.00	0.00	0.00	0.00	—	0.00	0.00	0.00	0.00	0.00
A3-10	0.04	0.02	0.04	0.02	0.02	0.02	0.02	0.02	0.00	—	0.02	0.02	0.02	0.02
A3-11	0.04	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.00	0.02	—	0.02	0.02	0.02
A3-12	0.04	0.02	0.04	0.04	0.02	0.02	0.02	0.02	0.00	0.02	0.02	—	0.00	0.00
A3-13	0.04	0.02	0.04	0.04	0.02	0.02	0.02	0.02	0.00	0.02	0.02	0.00	—	0.00
A3-14	0.04	0.02	0.04	0.04	0.02	0.02	0.02	0.02	0.00	0.02	0.02	0.00	0.00	—

Table 15. Input Data for the Four Scenarios in Sewer System Case

Activity	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	Operating priority	Assigned resource	Operating priority	Assigned resource	Operating priority	Assigned resource	Operating priority	Assigned resource
(a) Activity group: A1								
A1-1	1	R1-1	1	R1-1	1	R1-1	1	R1-1
A1-2	2	R1-1	2	R1-2	2	R1-1	2	R1-2
A1-3	3	R1-1	3	R1-1	3	R1-1	3	R1-1
A1-4	4	R1-1	4	R1-2	4	R1-1	4	R1-2
A1-5	5	R1-1	5	R1-1	5	R1-1	5	R1-1
A1-6	6	R1-1	6	R1-2	6	R1-1	6	R1-2
A1-7	7	R1-1	7	R1-1	7	R1-1	7	R1-1
A1-8	8	R1-1	8	R1-2	8	R1-1	8	R1-2
A1-9	9	R1-1	9	R1-1	9	R1-1	9	R1-1
A1-10	10	R1-1	10	R1-2	10	R1-1	10	R1-2
A1-11	11	R1-1	11	R1-1	11	R1-1	11	R1-1
A1-12	12	R1-1	12	R1-2	12	R1-1	12	R1-2
A1-13	13	R1-1	13	R1-1	13	R1-1	13	R1-1
A1-14	14	R1-1	14	R1-2	14	R1-1	14	R1-2
(b) Activity group: A2								
A2-1	1	R2-1	1	R2-1	1	R2-1	1	R2-1
A2-2	2	R2-1	2	R2-2	2	R2-1	2	R2-2
A2-3	3	R2-1	3	R2-1	3	R2-1	3	R2-1
A2-4	4	R2-1	4	R2-2	4	R2-1	4	R2-2
A2-5	5	R2-1	5	R2-1	5	R2-1	5	R2-1
A2-6	6	R2-1	6	R2-2	6	R2-1	6	R2-2
A2-7	7	R2-1	7	R2-1	7	R2-1	7	R2-1
A2-8	8	R2-1	8	R2-2	8	R2-1	8	R2-2
A2-9	9	R2-1	9	R2-1	9	R2-1	9	R2-1
A2-10	10	R2-1	10	R2-2	10	R2-1	10	R2-2
A2-11	11	R2-1	11	R2-1	11	R2-1	11	R2-1
A2-12	12	R2-1	12	R2-2	12	R2-1	12	R2-2
A2-13	13	R2-1	13	R2-1	13	R2-1	13	R2-1
A2-14	14	R2-1	14	R2-2	14	R2-1	14	R2-2
(c) Activity group: A3								
A3-1	1	R3-1	1	R3-1	1	R3-1	1	R3-1
A3-2	2	R3-1	2	R3-2	2	R3-1	2	R3-2
A3-3	3	R3-1	3	R3-1	3	R3-1	3	R3-1
A3-4	4	R3-1	4	R3-2	4	R3-1	4	R3-2
A3-5	5	R3-1	5	R3-1	5	R3-1	5	R3-1
A3-6	6	R3-1	6	R3-2	6	R3-1	6	R3-2
A3-7	7	R3-1	7	R3-1	7	R3-1	7	R3-1
A3-8	8	R3-1	8	R3-2	8	R3-1	8	R3-2
A3-9	9	R3-1	9	R3-1	9	R3-1	9	R3-1
A3-10	10	R3-1	10	R3-2	10	R3-1	10	R3-2
A3-11	11	R3-1	11	R3-1	11	R3-1	11	R3-1
A3-12	12	R3-1	12	R3-2	12	R3-1	12	R3-2
A3-13	13	R3-1	13	R3-1	13	R3-1	13	R3-1
A3-14	14	R3-1	14	R3-2	14	R3-1	14	R3-2

the construction of each manhole. Fig. 9 illustrates the network layout of the project, and shows the ID number, activity number, and elevation of each manhole. Manholes with an ID number of MH-0X are on the main pipeline, while those with an ID number of MH-0X-XX are on the branch line. The figure also shows the activity number, inner diameter (Φ), slope (S), length (L), upper elevation (U), and lower elevation (D) of the pipe in each pipeline segment.

Fig. 10 shows the activities of each of the three workgroups and their logical relationships. Within each workgroup, the priority of a sequence of activities is a decision variable decided by the project planner and/or scheduler. Table 6 lists the main equipment

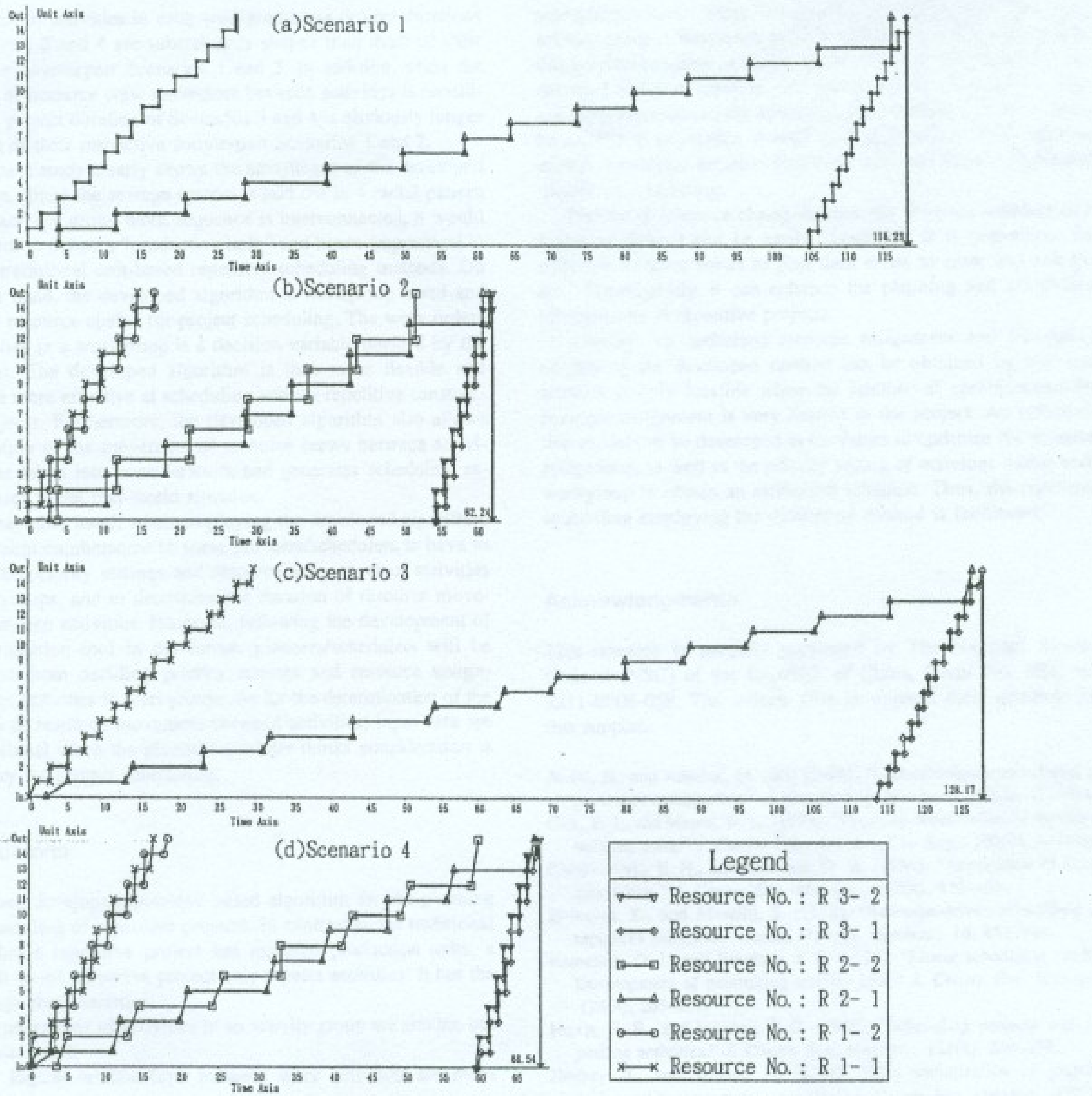

Fig. 11. Scheduling results for four scenarios in sewer system case

used by each of the three workgroups during construction. It is assumed in this case that two work crews, with different skill levels and working efficiency, are available to each workgroup.

Tables 7 and 8 list activity duration and the duration of mobilization/demobilization of work crews in/out of the job site. This information was obtained by interviewing the subcontractors and equipment providers. Since two work crews with different skill levels perform activities in each workgroup, two sets of durations are given for the activities for each workgroup: one for work crew 1 and the other for work crew 2. Furthermore, Tables 9–14 lists respective durations for the movement of resource crews between activities for resource crews R1-1, R1-2, R2-1, R2-2, R3-1, and R3-2.

The four scenarios listed below are tested in the scheduling of the project. Table 15 shows these scenarios' respective data inputs, including priority settings and resource assignment.

1. Only one resource type is used for each workgroup. In this case, only R1-1, R2-1, and R3-1 are employed in workgroups A1, A2, and A3, respectively. The duration of the movement of resource crews between activities is not considered.
2. One more resource type is used for each workgroup. R1-2, R2-2, and R3-2 are also employed in workgroups A1, A2, and A3, respectively. The duration of the movement of resource crews between activities is likewise not considered.
3. Same conditions as Scenario 1, but with the duration of the movement of resource crews between activities considered.
4. Same conditions as Scenario 2, but with the duration of the movement of resource crews between activities considered.

Fig. 11 shows scheduling results for the four scenarios. Total project duration for Scenarios 1, 2, 3, and 4, respectively, is 118.29, 62.24, 128.17, and 68.54 days. With two crews working in parallel on activities in each workgroup, the project durations of Scenarios 2 and 4 are substantially shorter than those of their respective counterpart Scenarios 1 and 3. In addition, when the duration of resource crew movement between activities is considered, the project duration of Scenarios 3 and 4 is obviously longer than that of their respective counterpart Scenarios 1 and 2.

This case study clearly shows the advantages of the developed algorithm. Since the sewage system is laid out in a radial pattern and the activity group work sequence is interconnected, it would be difficult to define a "production unit," and hence impractical to employ traditional unit-based repetitive scheduling methods. On the other hand, the developed algorithm is workgroup based and employs resource chains for project scheduling. The work orders of activities in a workgroup is a decision variable decided by the scheduler. The developed algorithm is thus more flexible and therefore more effective at scheduling various repetitive construction projects. Furthermore, the developed algorithm also allows the duration of the movement of resource crews between activities to be taken into consideration, and generates scheduling results closer to the real-world situation.

On the other hand, when employing the developed algorithm, it may seem cumbersome to some planners/schedulers to have to decide the priority settings and resource assignment of activities in workgroups, and to determine the duration of resource movement between activities. However, following the development of an optimization tool in the future, planners/schedulers will be exempted from deciding priority settings and resource assignments for activities in workgroups. As for the determination of the duration of resource movement between activities, input data are only optional when the planner/scheduler thinks consideration is necessary for project scheduling.

Conclusions

This work develops a non-unit-based algorithm for the planning and scheduling of repetitive projects. In contrast to the traditional view, that a repetitive project has repeated production units, a non-unit-based repetitive project only repeats activities! It has the following characteristics:

- The operations of activities in an activity group are similar, but not identical;
- The logical relationships between work activities are more generalized;
- There is no "hard logic" relationship between activities in the same activity group;
- Varied working crews can be employed within each activity group; and
- Cost and time for routing the various resource crews among production units is considered.

One sample case and one case study of a sewer system project, each with different scenarios, are tested to show that the setting of different operating priorities and resource assignment for activities in an activity group may have a significant impact on the scheduling results. Since the priority of similar activities in an activity group is frequently not constrained in real world practice, this becomes another decision variable that the scheduler or planner must make. In addition, the testing results show that, by adding more resources to the operation, the schedule will most likely be expedited shortening overall project duration. This becomes another important decision parameter that will have a significant impact on scheduling.

The use of resource chains to show the progress schedule of a repetitive project can be easily visualized. It is convenient for different resource crews to plan their times to enter and exit the site. Consequently, it can enhance the planning and scheduling effectiveness at repetitive projects.

Although an optimized resource assignment and scheduling employing the developed method can be obtained by trial and error, it is only feasible when the number of combinations for resource assignment is very limited in the project. An optimization model can be developed in the future to optimize the resource assignment, as well as the priority setting of activities within each workgroup to obtain an optimized schedule. Thus, the repetitive scheduling employing the developed method is facilitated.

Acknowledgments

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國立雲林科技大學
95 學年度博士班招生入學考試試題

所別：工程科技研究所
科目：工程數學 (丁)

1. Medical researchers have developed a new artificial heart constructed primarily of titanium and plastic. The heart will last and operate almost indefinitely once it is implanted in the patient's body, but the battery pack needs to be recharged about every four hours. A random sample of 50 battery packs is selected and subjected to a life test. The average life of these batteries is 4.05 hours. Assume that battery life is normally distributed with standard deviation $\sigma = 0.2$ hour.
   (a) Is there evidence to support the claim that mean battery life exceeds 4 hours? Use $\alpha = 0.05$. What is the P-value for this test? (10%)
   (b) Compute the power of the test if the true mean battery life is 4.5 hours. (10%)
   (c) What sample size would be required to detect a true mean battery life of 4.5 hours if we wanted the power of the test to be at least 0.9? (10%)

2. Of 1000 randomly selected cases of lung cancer, 823 resulted in death within 10 years.
   (a) Construct a 95% two-sided confidence interval on the death rate from lung cancer. (10%)
   (b) How large a sample would be required to be at least 95% confident that the error in estimating the 10-year death rate from lung cancer is less than 0.03? (10%)

3. A hot metal ball (T represents its temperature at any instant time t) was inserted into a bucket of cold water (T_m represents its temperature at any instant time t). When time past by from t0 to t, the temperature of the metal ball decreased from T_0 into T while the water temperature increased from T_{m0} into T_m. Assume a, a_m denote the heat constants of the metal ball and the water respectively. Please list the necessary (ordinary differential) equations and find out the temperature variation function of the metal ball. (25%)

4. Assume there are two equal-size continuous stirred tank reactors (CSTRs), T_1 and T_2 (see **Fig. 1**). In the beginning, T_1 contains 100 gal H_2O and T_2 contains 150 lb NaOH with 100 gal water. Later the pumps were powered on, a NaOH stream with a flow rate of 6 gal/min and concentration of 1 lb/gal was pumped into T_1. At the same time, the content of T_1 was pumped into T_2 with a flow rate of 8 gal/min; the outlet of T_2 was split into two streams, one flowed back to the tank T_2 and the other flowed to the downstream process. Please calculate the NaOH content of T_1 and T_2 as a function of time. (25%)

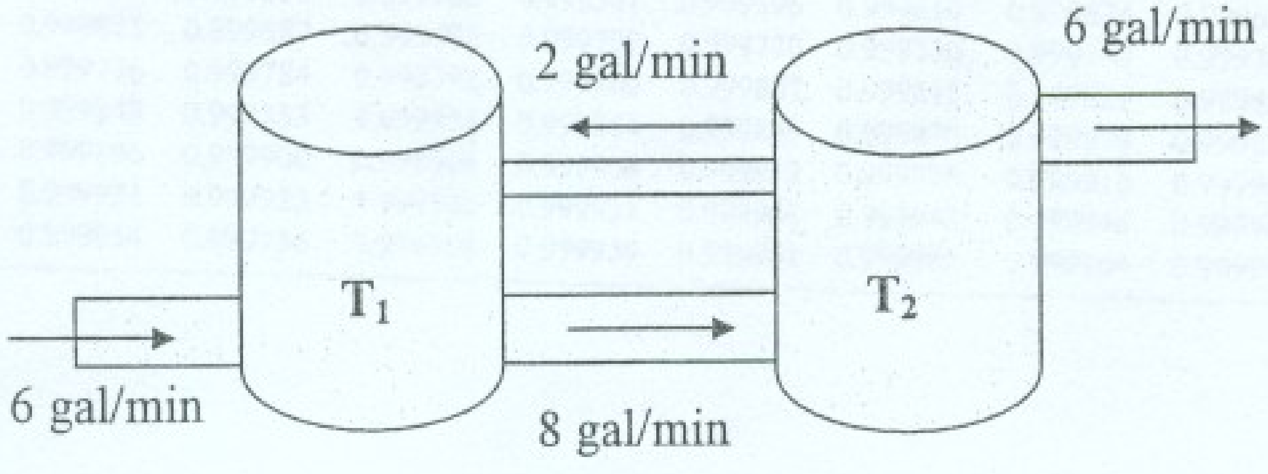

Fig. 1

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所別：工程科技研究所
科目：工程數學（丁）

$$\Phi(z) = P(Z \le z) = \int_{-\infty}^{z} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}u^2}\, du$$

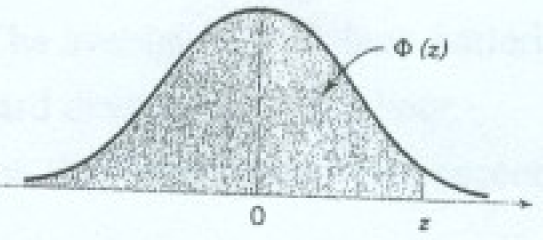

Table III Cumulative Standard Normal Distribution (*continued*)

z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.500000	0.503989	0.507978	0.511967	0.515953	0.519939	0.532922	0.527903	0.531881	0.535856
0.1	0.539828	0.543795	0.547758	0.551717	0.555760	0.559618	0.563559	0.567495	0.571424	0.575345
0.2	0.579260	0.583166	0.587064	0.590954	0.594835	0.598706	0.602568	0.606420	0.610261	0.614092
0.3	0.617911	0.621719	0.625516	0.629300	0.633072	0.636831	0.640576	0.644309	0.648027	0.651732
0.4	0.655422	0.659097	0.662757	0.666402	0.670031	0.673645	0.677242	0.680822	0.684386	0.687933
0.5	0.691462	0.694974	0.698468	0.701944	0.705401	0.708840	0.712260	0.715661	0.719043	0.722405
0.6	0.725747	0.729069	0.732371	0.735653	0.738914	0.742154	0.745373	0.748571	0.751748	0.754903
0.7	0.758036	0.761148	0.764238	0.767305	0.770350	0.773373	0.776373	0.779350	0.782305	0.785236
0.8	0.788145	0.791030	0.793892	0.796731	0.799546	0.802338	0.805106	0.807850	0.810570	0.813267
0.9	0.815940	0.818589	0.821214	0.823815	0.826391	0.828944	0.831472	0.833977	0.836457	0.838913
1.0	0.841345	0.843752	0.846136	0.848495	0.850830	0.853141	0.855428	0.857690	0.859929	0.862143
1.1	0.864334	0.866500	0.868643	0.870762	0.872857	0.874928	0.876976	0.878999	0.881000	0.882977
1.2	0.884930	0.886860	0.888767	0.890651	0.892512	0.894350	0.896165	0.897958	0.899727	0.901475
1.3	0.903199	0.904902	0.906582	0.908241	0.909877	0.911492	0.913085	0.914657	0.916207	0.917736
1.4	0.919243	0.920730	0.922196	0.923641	0.925066	0.926471	0.927855	0.929219	0.930563	0.931888
1.5	0.933193	0.934478	0.935744	0.936992	0.938220	0.939429	0.940620	0.941792	0.942947	0.944083
1.6	0.945201	0.946301	0.947384	0.948449	0.949497	0.950529	0.951543	0.952540	0.953521	0.954486
1.7	0.955435	0.956367	0.957284	0.958185	0.959071	0.959941	0.960796	0.961636	0.962462	0.963273
1.8	0.964070	0.964852	0.965621	0.966375	0.967116	0.967843	0.968557	0.969258	0.969946	0.970621
1.9	0.971283	0.971933	0.972571	0.973197	0.973810	0.974412	0.975002	0.975581	0.976148	0.976705
2.0	0.977250	0.977784	0.978308	0.978822	0.979325	0.979818	0.980301	0.980774	0.981237	0.981691
2.1	0.982136	0.982571	0.982997	0.983414	0.983823	0.984222	0.984614	0.984997	0.985371	0.985738
2.2	0.986097	0.986447	0.986791	0.987126	0.987455	0.987776	0.988089	0.988396	0.988696	0.988989
2.3	0.989276	0.989556	0.989830	0.990097	0.990358	0.990613	0.990863	0.991106	0.991344	0.991576
2.4	0.991802	0.992024	0.992240	0.992451	0.992656	0.992857	0.993053	0.993244	0.993431	0.993613
2.5	0.993790	0.993963	0.994132	0.994297	0.994457	0.994614	0.994766	0.994915	0.995060	0.995201
2.6	0.995339	0.995473	0.995604	0.995731	0.995855	0.995975	0.996093	0.996207	0.996319	0.996427
2.7	0.996533	0.996636	0.996736	0.996833	0.996928	0.997020	0.997110	0.997197	0.997282	0.997365
2.8	0.997445	0.997523	0.997599	0.997673	0.997744	0.997814	0.997882	0.997948	0.998012	0.998074
2.9	0.998134	0.998193	0.998250	0.998305	0.998359	0.998411	0.998462	0.998511	0.998559	0.998605
3.0	0.998650	0.998694	0.998736	0.998777	0.998817	0.998856	0.998893	0.998930	0.998965	0.998999
3.1	0.999032	0.999065	0.999096	0.999126	0.999155	0.999184	0.999211	0.999238	0.999264	0.999289
3.2	0.999313	0.999336	0.999359	0.999381	0.999402	0.999423	0.999443	0.999462	0.999481	0.999499
3.3	0.999517	0.999533	0.999550	0.999566	0.999581	0.999596	0.999610	0.999624	0.999638	0.999650
3.4	0.999663	0.999675	0.999687	0.999698	0.999709	0.999720	0.999730	0.999740	0.999749	0.999758
3.5	0.999767	0.999776	0.999784	0.999792	0.999800	0.999807	0.999815	0.999821	0.999828	0.999835
3.6	0.999841	0.999847	0.999853	0.999858	0.999864	0.999869	0.999874	0.999879	0.999883	0.999888
3.7	0.999892	0.999896	0.999900	0.999904	0.999908	0.999912	0.999915	0.999918	0.999922	0.999925
3.8	0.999928	0.999931	0.999933	0.999936	0.999938	0.999941	0.999943	0.999946	0.999948	0.999950
3.9	0.999952	0.999954	0.999956	0.999958	0.999959	0.999961	0.999963	0.999964	0.999966	0.999967