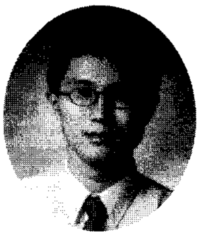
Load Redistribution of Prestressed Concrete Girder Bridges during the Bearing Replacement



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ABSTRACT

In the replacement of bearing system of bridges, the jacking work to secure work spaces may cause damage of the superstructure, hence the behavior of superstructure by the jacking force must be considered. Especially, in prestressed concrete I-type girder bridges, considering the stress concentration at the girder and the load redistribution of superstructure, the allowable jacking force and jacking sequence have to be determined. In this study, an analytical method is proposed to calculate the jacking force and overall jacking sequence for the replacement of bearing system without any damage to the superstructure. The stress concentration at the girder and load redistribution of the deck due to jacking force are considered to compute the allowable jacking force for each girder and overall jacking sequence for girders in the deck. Using the solution algorithm developed in this study, the optimum jacking sequence and required jacking force for the prestressed concrete I-type girder bridge having the standard sections are calculated.

Keywords : bearing system, deck behavior, maintenance, repairs, structure analysis, structural safety

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1. INTRODUCTION

The bearing system is an important component of bridge enable to transfer a load coming from the superstructure to the substructure, and to allow expansion of the superstructure. Consequently, a functional defect of bearing system may cause damage of the substructure as well as superstructure. For these reasons, functionally obsolete bearing system has to be repaired or replaced immediately.

In the replacement of bearing system, the jacking work of superstructure to secure work spaces has to be done with caution. Especially, in case of jacking using the hydraulic jack in prestressed concrete I-type girder bridges, the girder and deck can be damaged during the replacement due to the transverse bending moment introduced by jacking force. However, in practice, the computations of jacking force and the jacking sequence are generally determined by the experience of engineers without any consideration of structural response. The excessive jacking force can be introduced to secure required work spaces, hence the superstructure will be often damaged. In addition, the replacement of bearing system has to be completed possibly soon to minimize the bridge closure. However, the current experience oriented replacement work requires a lot times.

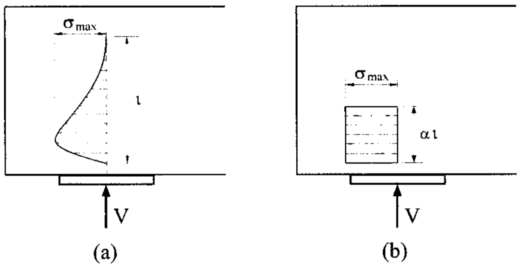
As mentioned in the above, the reason which the existing jacking work has been dependent on the experience of engineers is why there has no been systematical study about how to compute the jacking force and sequence considering the behavior of jacked superstructure so far. Therefore, an analytical study for the replacement of bearing system is strongly demanded.

This study proposes a solution algorithm to compute the jacking force and jacking sequence for the replacement of the bearing system without any damage to the superstructure of prestressed concrete I-type girder bridges considering the load redistribution of the superstructure. In order to compute the required jacking force, the stress concentration at the girder due to jacking force is also considered. Futhermore, optimum jacking sequence for the girders is determined by the analysis of the behavior of superstructure subjected to the jacking of superstructure.

2. BEHAVIOR OF JACKED SUPERSTRUCTURE

2.1 Behavior of Girder

The jacking work of prestressed concrete girder bridge is generally performed at the support of girders, hence the support is subjected to a concentrated load in upward direction. The concentrated load applied at the support of girder develops the compressive bearing stress in transverse direction as well as tensile burst stress in the longitudinal direction of the girder. The distribution of tensile burst stress developed at the girder support is shown in Fig.1(a). In the figure, $\sigma_{\max}$ is the maximum burst stress and V the jacking force, and l the height of nonuniform stress block.



(a) Actual Distribution (b) Equivalent Rectangular Distribution

Fig.1 Distribution of Tensile Stresses at Jacking Force:

The nonuniform distribution of burst stresses may be replaced with an equivalent uniform stress distribution, as illustrated in Fig.1(b). The effective height, which is denoted by $\alpha \cdot l$ in Fig.1(b), is an equivalent height of the uniform stress block acts, whose resultant force is the same as that of a nonuniform stress block shown in Fig.1(a).

In this case, a tensile force per unit length of the support at the girder is given by

$$Z = \sigma_{\max}(\alpha \cdot l)b \tag{1}$$

in which b is the width of girder.

In order to compute a tensile force at the girder support using Eq. (1), the distribution of burst stresses is needed. In this study, the distribution of burst stresses at the anchorage of prestressed concrete girder by the prestressing force is utilized for this purpose[1)].

Burst stresses introduced around the anchorage of prestressed concrete girder, and its distribution is shown in Fig.2. In the figure, σ_y is the burst stress and σ_0 is the average axial stress at the girder. The distribution of burst stresses varies with the ratio of the width of anchorage plate and height of girder, a/d.

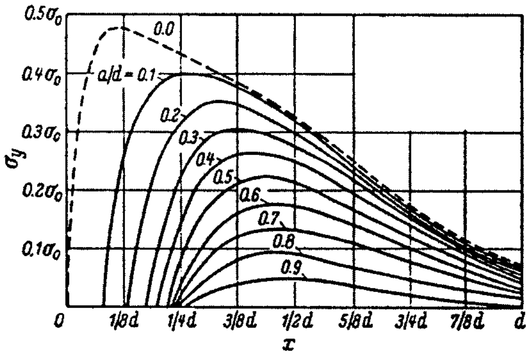


Fig.2 Distribution of Tensile Stresses in Burst Area of Prestressed Concrete Girder at Prestressing Force

Leonhardt[2)] has proposed an approximate equation to compute a tensile burst force at the girder due to the prestressing force as

$$Z = 0.3\,V\left(1-\frac{a}{d}\right) \tag{2}$$

where V is the prestressing force. Using Eqs. (1) and (2), the relationship between the jacking force and the maximum burst stress can be obtained as

$$V = \frac{\sigma_{\max}(\alpha \cdot l)}{0.3\left(1-\frac{a}{d}\right)} \tag{3}$$

In Eq. (3), since the maximum burst stress cannot exceed the allowable tensile strength of concrete, the allowable jacking force at the girder support becomes

$$V = \frac{\sigma_{ta}(\alpha \cdot l)}{0.3\left(1-\frac{a}{d}\right)} \tag{4}$$

where σ_{ta} is the allowable tensile strength of concrete.

Based on the distribution of burst stresses in Fig.2, the effective height of uniform stress block at the girder support can be computed as

$$\alpha \cdot l = \frac{1}{\sigma_{\max}} \int \sigma_y \, dx \qquad (5)$$

The distribution of burst stresses changes by the values of a/d, and the value of coefficient α in Eq. (5) is given in Table 1.

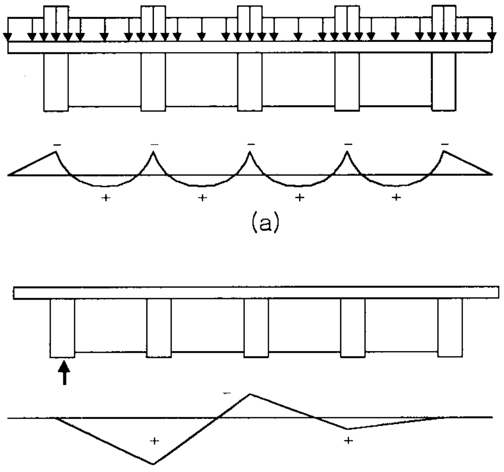
Based on the linear regression analysis for the data in Table 1, an empirical equation to compute coefficient α for various a/d can be derived and given by

$$\alpha = 0.5439 - 0.1038\left(\frac{a}{d}\right) \qquad (6)$$

2.2 Behavior of Deck

In case of jacking at the supports, the bending moment at the jacked superstructure has maximum value at the deck and cross beam near the supports rather than the mid-span of the bridge, accordingly the bending moment has to be calculated on the basis of the deck and cross beam near the supports.

By considering bending moments in transverse direction, prior to the jacking, the deck above the cross beam shown in Fig.3(a) is subjected to the negative bending moment by the dead load. On the other hand, the deck under the jacking force is subjected to the positive bending moment as shown in Fig.3(b). Consequently, depends on the magnitude and position of jacking force, transverse members are in turns subjected to the positive and negative bending moments.



(a)

(b)

Fig.3 Moment Diagrams of Slab Under Dead Load and Jacking Force

At this time, the overall section of member is effective to the bending moments applied to deck and cross beams, and tensile stresses of the section cannot exceed the allowable tensile strength of concrete. This is aimed at preventing the superstructure from damaging during the replacement of bearing system.

Table 1 Coefficient α for a/d

a/d	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
α	0.4407	0.4356	0.4621	0.5286	0.4759	0.5081	0.5217	0.5482	0.4970

3. ANALYSIS METHOD

The jacking force has to be confined that all stresses at the superstructure may not exceed the allowable tensile strength of concrete. That is, the principle of superposition may be applied to analysis by assuming the elastic behavior of the structure.

The jacking force to lift the superstructure mainly affects the transverse direction than the longitudinal direction of the superstructure. This behavior is similar to that of the ununiform settlement of supports. Hence, the stresses influence the structures are the stresses in the transverse direction, especially are bearing stresses at the supports.

Fig.4 shows the profile of transverse displacement of superstructure by the jacking sequence, in which Fig.4(a) shows the original configuration. Fig.4(b) shows the behavior of superstructure when continuously jacked to replace the first bearing system to the left. When the support is further jacked, the reaction force at the adjacent support is decreased, eventually no reaction force is applied, and then this support becomes a free-end as shown in Fig.4(c).

The stresses at the superstructure need to be check during the increment of the jacking force. If the stress level caused by the jacking force reaches the allowable tensile strength of concrete or the limit causes the partial failure of girder, the jacking is stopped, and then the jacking of adjacent support follows. At this time, the displacement of the first jacked support does not decrease as shown in Fig.4(d) because the jack itself acts as a new support.

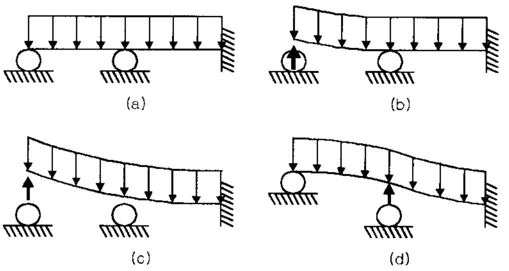


Fig.4 Transverse Displacement of Deck at Jacking Force

For the illustrative purpose, the proposed analysis method is applied to a five-girder bridge to analyse the behavior of superstructure by the jacking force. In this case, the possible combination of jacking points and jacking sequence is thirty-two. However, the displacement at the jacking point does not decrease as shown in Fig.5, so all possible cases may be twenty-five as provided in Table 2.

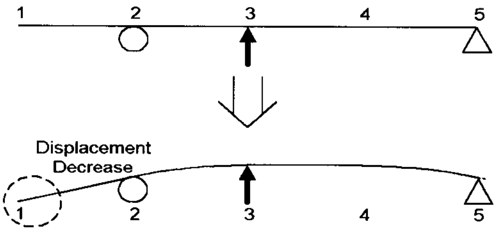


Fig.5 Inadmissible Case

The jacking at a support affects adjacent supports. When the jacking force is applied at any support, the displacement, reaction, and moment of adjacent supports can be computed. This procedure is illustrated in Table 3.

Table 2 Change of Boundary Conditions for Different Jacking Scheme

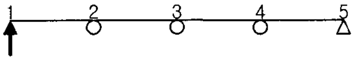
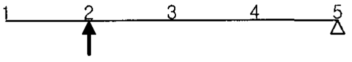
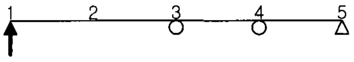
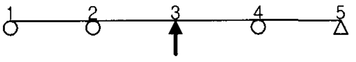
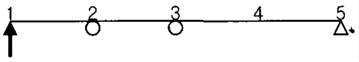
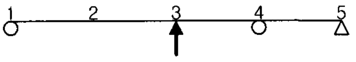
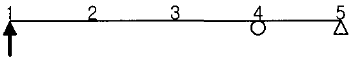
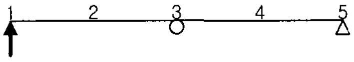
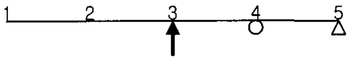
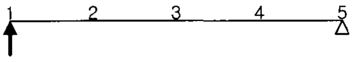
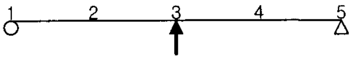
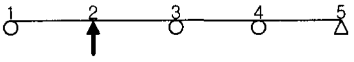
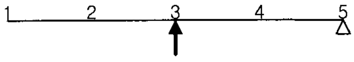
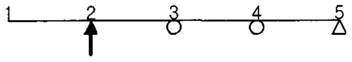
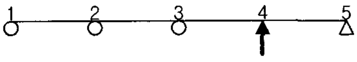
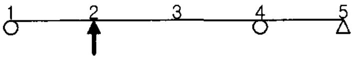
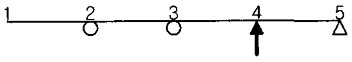
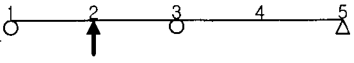
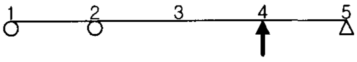
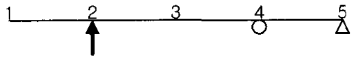
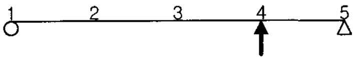
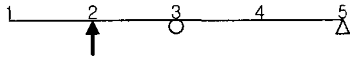
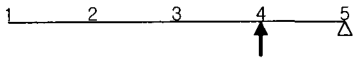
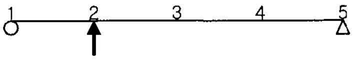
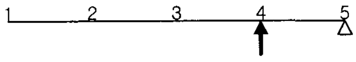
No.	Load Position	CASE	No.	Load Position	CASE
1	1		14	2	
2	1		15	3	
3	1		16	3	
4	1		17	3	
5	1		18	3	
6	1		19	3	
7	2		20	3	
8	2		21	4	
9	2		22	4	
10	2		23	4	
11	2		24	4	
12	2		25	4	
13	2		25	4	

Table 3 Displacements, Reactions, and Bending Moments at Support

Support	Displacement	Reaction	Moment
1	$D_1 = P \times d_{i1}$	$R_1 = r_1 + P \times r_{i1}$	$M_1 = m_1 + P \times m_{i1}$
2	$D_2 = P \times d_{i2}$	$R_2 = r_2 + P \times r_{i2}$	$M_2 = m_2 + P \times m_{i2}$
3	$D_3 = P \times d_{i3}$	$R_3 = r_3 + P \times r_{i3}$	$M_3 = m_3 + P \times m_{i3}$
4	$D_4 = P \times d_{i4}$	$R_4 = r_4 + P \times r_{i4}$	$M_4 = m_4 + P \times m_{i4}$
5	$D_5 = P \times d_{i5}$	$R_5 = r_5 + P \times r_{i5}$	$M_5 = m_5 + P \times m_{i5}$

In Table 3, P is the jacking force, d_{ij} the displacement at joint j under the unit load at joint i, r_{ij} the reaction at joint j under the unit load at joint i, m_{ij} the bending moment at joint j under the unit load at joint i, M_i the bending moment at joint i, D_i the displacement at joint i, R_i the reaction at joint i, r_i the reaction at joint i due to the dead load, and m_i the bending moment at joint i due to the dead load.

If moment M and reaction R at the supports by jacking force satisfy the conditions in Eqs. (6) and (7), the prestressed concrete girder and deck may not be damaged.

$$R_i < R_{a1} \tag{6a}$$

$$R_i < R_{a2} \tag{6b}$$

where Ri is the reaction at joint i, R_{a1} is the allowable reaction by the allowable burst stress proposed in Eq. (4), and R_{a2} is the allowable reaction by the allowable bearing stress, which is specified in the Specifications[3].

$$M_a' < M_i < M_a \tag{7}$$

where M_a' is the maximum allowable negative moment, M_i the moment at joint I, and M_a the maximum allowable positive moment.

4. SOLUTION ALGORITHM

A flowchart of the overall solution scheme is presented in Fig.6. The solution process begins with the input data, which consists of moment, reaction, and deflection at the support due to the unit load. After selecting a jacking point, the load is gradually increased and the reaction and moment at each joint are computed. If the computed reaction and moment satisfy the conditions in Eqs. (6) and (7), the obtained displacement at the joint is compared with the prescribed tolerance for work spaces enough to replace the bearing system.

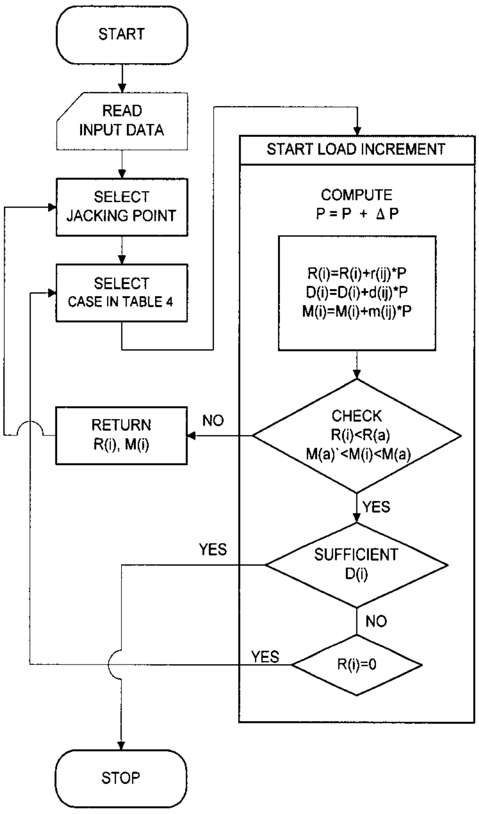


Fig.6 Flow Chart for Analysis Algorithm

If an enough work space is obtained, the solution process is advanced with next joint. Otherwise, joints of zero reaction are checked. If there is any joint of zero reaction, a case suitable for following load steps is selected and then a load is continuously increased. Otherwise, a load is continuously increased. If the reaction and moment do not satisfy the conditions in Eqs. (6) and (7), they are returned and transformed to the reaction and moment of previous step for the safety of superstructure, and then a new joint begins to be jacked. The above process is repeated until a work space to replace the bearing system is secured.

5. ILLUSTRATIVE EXAMPLE

A prototype of bridge under service is analysed to verify the analysis program developed in this study. The bridge selected herein is the post-tensioned concrete bridge having five I-type girders, the design live load is DB-24 (1.33 times larger than HS-20), the length of girder is 30m and the width of bridge is 11.5m. As shown in Fig.7, the superstructure of bridge is modeled based on the grillage method of analysis[4].

5.1 Assumptions

The following assumptions are made in the analysis.

(1) The superstructure is subjected to the dead load only since the replacement of bearing system is executed under the traffic control.

(2) The size of loading plate is 300 mm× 300 mm.

(3) The displacement of jacked girder does not decrease.

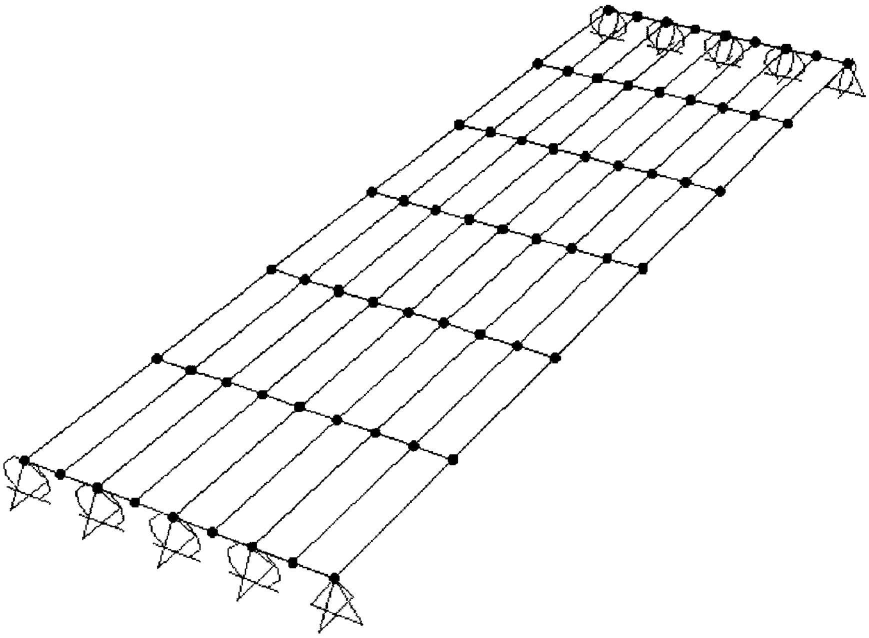


Fig.7 Finite Element Model Used in Analysis

(4) The required work space for the bearing replacement is 2 mm.

5.2 Material Properties and Allowable Stresses

(1) Concrete design strength of girder: 37.0 MPa
(2) Concrete design strength of deck: 24.0 MPa
(3) Allowable tensile strength of concrete: 3.08 MPa
(4) Elastic modulus of concrete: 28.84 GPa

5.3 Allowable Stresses and Bending Moments

(1) Allowable reaction by burst stress: 1,539.8 kN
(2) Allowable reaction by bearing stress: 1,831.6 kN
(3) Allowable positive moment of cross beam at support: 921.0 kN·m
(4) Allowable negative moment of cross beam at support: -1,278.6 kN·m

5.4 Results of Analysis

The analysis results of this example are summarized in Table 4.

Step 0 is a case under the dead load, and joint reactions are the reactions at each support. Shaded cells in the table show the upward displacements and upward jacking forces at joints. That is, when joint 1 is jacked up by 1,068 kN in Step 1, the reactions and displacements at each joint are changed as provided in Table 4. Herein in order to secure a work space of 2 mm to replace the bearing system at exterior girder, Steps 1 to 5 are performed, and in order to replace the bearing system of the first interior girder, Steps 1 to 9 has to be performed. Similarly, in order to replace the second interior girder, Steps 1 to 13 has to be performed.

When a positive moment at joint 2 in Step 1 reaches the limit, in Step 2 a burst stress at joint 2 reaches at the limit, and also in Step 3 a burst stress at joint 3 reaches the limit. In general, the results of analysis reveal that the important factors which have influence on the behavior of structures in the replacement of bearing system are burst stresses of girder and positive moments of cross beams at the support. On the other hand, the influence of bearing stresses and negative bending moments on the structural response is not significant.

This study computes and proposes the jacking sequence for other types of prestressed concrete girder bridges having the standard sections as well as this example. Although, the results slightly differ from by the bridge classes and the length of girders, they might be calculated by the same method as an example of this paper. The results of analysis for other class of prestressed concrete I-type girder bridges are well summarized in the reference[5].

6. CONCLUSIONS

This study proposes a solution algorithm to compute the jacking force and overall jacking sequence for the replacement of the bearing system without any damage to the superstructure of prestressed concrete girder bridges.

Table 4 Results of Analysis

	Joint	1	2	3	4	5		Joint	1	2	3	4	5
STEP 0	R (KN)	633	587	579	587	633	STEP 7	R (KN)	740	0	1540	0	737
	M (KN · m)	1	-11	-07	-11	1		M (KN · m)	2	260	-819	245	7
	D (mm)	0	0	0	0	0		D (mm)	2.082	1.632	1.201	0.594	0
STEP 1	R (KN)	1068	0	399	965	585	STEP 8	R (KN)	113	1540	483	0	878
	M (KN · m)	-7	921	568	-155	-1		M (KN · m)	2	-1140	-158	551	7
	D (mm)	0.682	0.201	0	0	0		D (mm)	2.082	1.793	1.201	0.532	0
STEP 2	R (KN)	286	1540	0	281	917	STEP 9	R (KN)	1072	0	877	0	1065
	M (KN · m)	4	-883	551	597	-1		M (KN · m)	-14	921	549	902	-0
	D (mm)	0.682	0.522	0.195	0	0		D (mm)	3.491	2.203	1.201	0.464	0
STEP 3	R (KN)	741	0	1540	0	743	STEP 10	R (KN)	1034	95	812	0	1074
	M (KN · m)	6	259	-803	249	1		M (KN · m)	-14	835	590	921	-0
	D (mm)	0.682	0.583	0.502	0.244	0		D (mm)	3.491	2.214	1.201	0.460	0
STEP 4	R (KN)	114	1540	483	0	884	STEP 11	R (KN)	740	0	1540	0	732
	M (KN · m)	6	-1140	-162	555	1		M (KN · m)	-1	260	-814	240	13
	D (mm)	0.682	0.744	0.502	0.183	0		D (mm)	3.491	2.682	1.903	0.942	0
STEP 5	R (KN)	1074	0	876	0	1071	STEP 12	R (KN)	113	1540	483	0	873
	M (KN · m)	-11	921	545	907	-6		M (KN · m)	-1	-1139	-153	546	13
	D (mm)	2.082	1.154	0.502	0.115	0		D (mm)	3.491	2.861	1.903	0.879	0
STEP 6	R (KN)	1045	70	828	0	1077	STEP 13	R (KN)	539	268	1540	0	664
	M (KN · m)	-11	857	575	921	-6		M (KN · m)	-1	-653	-607	327	13
	D (mm)	2.082	1.161	0.502	0.112	0		D (mm)	3.491	2.861	2.099	1.063	0

The developed program can be used in the practice as well.

Based on the results of analysis, several conclusions can be drawn and summarized in the following.

1) An empirical equation is derived to compute the effective height of uniform stress at the girder due to the jacking force, based on the linear regression analysis.
2) Considering the behavior of superstructure by the jacking force, the jacking sequence as well as the jacking force at the support is considered to be crucial factors influencing on the behavior of superstructure. Accordingly this study proposes the jacking sequence for the overall superstructure as well as the jacking force of each girder securable to the required work space with the safety of superstructure.
3) In case of replacing the bearing system, the bearing systems at the supports may rotate and/or move in lateral direction. It is recommended that the bearing system at the exterior girder needs to be fixed during the replacement to prevent movement at the support, considering the convenience of construction and

the safety of superstructure.

4) The allowable jacking force and overall jacking sequence calculated by the proposed method in this study are considered to be effectively used to replace the bearing system of prestressed concrete I-type girder bridges.

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