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# Analytical Prediction of Damping Coefficient-Vibration Amplitude Relationship Changes of Reinforced Concrete Bridge Piers

**Mais Adeeb Ghassoun*[1]** **Reem ALsehnawi[2]**

*1. Dr, lecturer, Faculty of Engineering, Wadi International University – Homs –Syria.
dr-maisghassoun@wiu.edu.sy

2. Dr, lecturer, Higher Institute of Earthquake Studies and Researches, Damascus University– Damascus –Syria.
reem1.salman@damascusuniversity.edu.sy

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## Abstract:

The dynamic parameters like damping ratio and natural frequency are crucial, to explain the dynamic behavior of structures and predict their responses to various vibration motions. The analytical approach is thought to have inherent flaws, since the dynamic properties of structures are typically predicted analytically and do not take into account changes in amplitude vibration. Although the majority of earlier experimental investigations sought how variations in vibration amplitude affect dynamic properties, analytical discussion of these changes has not been done yet. This analytical and numerical study was conducted to better understand the effect of excitation changes on damping ratio in dynamic analysis of reinforced concrete bridge piers using Abaqus 6.14 program. In order to do this, analytical prediction of the relationship between the damping ratio changes versus vibration amplitude changes were investigated. Then, modal analysis and dynamic analysis on tested bridge pier specimens were carried out considering the damping ratio changes. To find that, the analytical responses, after defining the damping changes function in the analytical model, were closer to the experimental responses than those with constant damping coefficient by comparing the acceleration responses of the pier model.

**Keywords:** Damping Coefficient 1, Free Vibration 2; Forced Vibration 3; Amplitude 4; RC Bridge's Pier 5.

# التنبؤ تحليلياً بعلاقة تغير معامل التخامد بدلالة تغير سعات الاهتزازات لركائز الجسور البيتونية المسلحة

**ميس أديب غصون*[1]    ريم الصحناوي[2]**

*[1]. دكتورة، مدرّسة في كليّة الهندسة– جامعة الوادي الدولية الخاصّة – حمص – سوريا.
dr-maisghassoun@wiu.edu.sy
[2]. مدرّسة في المعهد العالي للبحوث و الدراسات الزلزاليّة– جامعة دمشق– دمشق - سوريا.
reem1.salman@damascusuniversity.edu.sy

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## الملخص:

تعتبر الخصائص الديناميكيّة كنسبة التخامد والتردد الطبيعي من العوامل الأساسيّة للتعبير عن السلوك الديناميكي للمنشآت والتنبؤ باستجاباتها تحت تأثير مختلف الاهتزازات. نظراً لعدم إمكانية حساب معامل التخامد في مرحلة التصميم للمنشآت، فقد جرت العادة أن تُقدّر قيمته بشكل تقريبيّ. بالرغم من أن معظم الدراسات التجريبية السابقة تناولت تغيّر الخصائص الديناميكيّة مع تغيّر سعات الاهتزاز في التحليل الديناميكيّ للمنشآت، إلا أنه لم يتم التطرق حتى الآن لإيجاد علاقة رياضية تحكم هذا التغير تحليلياً. يقدم هذا البحث دراسة تحليليّة وعدديّة لركيزة جسريّة من البيتون المسلح باستخدام برنامج Abaqus لدراسة أثر تغيّر سعة الاهتزاز على نسبة التخامد والتردّد الطبيعيّ بإيجاد علاقات رياضيّة مبسّطة من خلال محاكاة تجربة الاهتزاز الحرّ في المرحلة المرنة على عينة الركيزة الجسرية السليمة، ومن ثم محاكاة تجربة الاهتزاز القسري للوصول للمرحلة اللدنة للعينة، يليها تطبيق الاهتزاز الحر على العينة المتشقّقة. ومن خلال مقارنة استجابات التسارع والانتقال للركيزة الجسرية، تبيّن أنّ الاستجابات الديناميكيّة التحليليّة الناجمة عن ادخال تابع تغيّر التخامد في التحليل أقرب إلى الاستجابات التجريبيّة من تلك الناجمة عن ادخال التخامد كقيمة ثابتة.

**الكلمات المفتاحية:** معامل التخامد1، الاهتزاز الحر 2، الاهتزاز القسري 3، سعةالاهتزاز4، الركائز الجسرية البيتونية المسلّحة 5.

## Introduction:

In order to verify the dynamic behavior of the structures while responding to high levels of vibration, vibration tests have become more common on structures over the past century. However, the expense, large equipment requirements, and significant effort required by this method, discourage researchers from using it. In order to avoid using vibration instruments as simulations and to replace vibration generation tests with effortless techniques. free vibration and circumferential vibration tests were used to identify structural dynamic behaviors. Given the significance of natural period in determining a structure's level of safety, the natural frequency was used as the governing norm in the structural characteristics. Many researchers worked on completing a vibration control study, such as working on the analysis of frequency data, which can be collected cheaply and are sensitive indicators of structural safety [1]. Othor researches have sought to track radiation damping in seismic response of buildings, and have discussed how radiation damping relates to the engineering properties of the structure [2]. Although, the abovementioned techniques can be used to examine the effects of the natural frequency and damping ratios dependency on the vibration amplitudes. The available analytical simulation, which relies on creating numerical models using well-known techniques for structures modelling, including the finite element method, is crucial for understanding the dynamic behavior of the structures.

## 1_Previous researches:

Many laboratory and in-situ experiments were conducted in previous studies to find techniques to assess the dynamic properties, some of these researches looked at how different types of installations' response capacities changed as a result of dynamic properties. It was discovered that the employment of free and circumferential vibration will offer a good alternative because it avoids damaging the structural elements, and saving money and time compared to massive forced vibration equipment. (M. Çlelebi etal. 1993) were investigated the dynamic characteristics of five buildings under high motions and low amplitudes [3]. They found that the seismic motion frequencies are useful for setting damping predictions based on forced vibration tests. (Fuqua et al. 1989) discovered that across the whole spectrum of prefabricated metal buildings, the dynamic properties are heavily dependent on the nonstructural parts' ability to respond [4].

(Tamura and Sagunama 1996) examined the evaluation of amplitude dependence with respect to the natural frequency and damping ratio of three towers subjected to strong winds. They proposed the RDT classified by peak amplitude for a direct effective evaluation that demonstrates the dependence of amplitude on dynamic properties [5]. (Alsehnawi et al. 2016) were conducted free vibration experiments and a shaking table experiment as part of an experimental investigation of reinforced concrete bridge pier. The dependency of the natural frequency and damping ration the acceleration amplitude was determined [6]. Many previous studies were discussed the effect of vibration amplitudes on the dynamic characteristics of reinforced concrete structures in several experimental researches. However, the analytical prediction of the influence of vibration amplitude on the dynamic characteristics and the dynamic behavior of bridge piers has not conducted yet.

## 2_Objective of the study:

The purpose of this study is to predict analytically the relationship between the damping ratio and the amplitude of vibration excitation of reinforced concrete bridge piers.

## 3_Methodology of the research:

An analytical and numerical research was done by using Abacus 6.14 program-based numerical simulation of three laboratory models that had previously been conducted at Utsunomiya University in Japan [6] [7] [8]. First of all, the experimental data from the three models was analyzed to expresses the relationship of the damping ratio with the acceleration amplitudes changes. Secondly, the damping ratio versus the natural frequency values at each time step were determined by solving the equilibrium equation for each model with fixed damping ratio and with variable damping ratio. Thirdly, the numerical models were solved in Abaqus 6.14 program. Here, the damping ratio against the frequency values were input at each time step. The analytical and experimental responses were compared. Finally, using 15% of Kushiro earthquake record, the dynamic analysis of the first model was done with constant and variable damping ratios.

depicted in Figure (7). The equation of this graph is illustrated in equation (2). Thereafter, the differential equation of motion, equation (1), was solved in order to conduct an analytical analysis of the model, taking into account the model is single degree of freedom system in programming the solution to determine the dynamic responses. The free vibration test was implemented by using an initial velocity at the instant of t = 0, ($u = 0$، $\dot{u} = \dot{u}_0$ , $\ddot{u} = 0$) with incremental time of $\Delta t$ = 0.023sec. In order to determine the analytical response value,ün+1=üexp, the acceleration response is calculated and compared to the maximum acceleration for each shock. The equation (2) was substituted in equation (1) to get the differential equation of motion in term of variable damping.

$$\ddot{\mathbf{u}} + 2\boldsymbol{\zeta}\boldsymbol{\omega}_{\mathbf{n}}\dot{}\mathbf{u} + \boldsymbol{\omega}_{\mathbf{n}}^{2}\mathbf{u} = \mathbf{0} \qquad (1)$$

ζ = 0.0305 **ü**0.2493: F (**ü**) = ζ (2)

In order to get the preceding equation to describe the overall changes in the damping ratio in terms of responses amplitude. Based on the equation that was found by processing the experimental and acceleration data. Thereafter, sequential approximation method was applied using Newmark equations to compute the response values (deformation, velocity, and acceleration) in each time step.

# 6. Numerical analysis:

## 6.1. Numerical model:

The modelling was carried out in Abaqus 6.14 [9] by simulating engineering, physical, and structural properties, as shown in Figures (10). Finite element mish with dimensions of (0.2 × 0.2 × 0.2) m3was used. In this study, the stress-strain relationship of concrete and steel depending on the fundamental relationships of the material properties [10] were shown in Figure (8) and Figure (9).

## 6.2. Model analysis:

### 6.2.1. Modal analysis:

Modal analysis was applied on the pier model by applying a triangular pulse in the weak direction of the cross-section, Figure (11), which depicts the impact of relatively strong forces over a brief period of time. Abaqus 6.14 was used to perform modal analysis in two scenarios: (1) constant damping ratio of ζ=0.05, (2) variable damping ratio. The ana-

# 4. The modelling

Three laboratory models were used in this study. The first model is a cantilever pier model, shown in Figure (1). It consists of a single column, a cap and a concrete block that expresses the weight of the bridge slab. The foundation of the pier was modeled as a concrete block [6]. The second model, in Figure (2), is the first model after reaching the collapse stage by applying Kushiro earthquake, and then strengthen it by carbon fiber sheets [8]. The third model is illustrated in Figure (3), the model is a single-span bridge. It consists of a reinforced concrete beam on two reinforced concrete piers. Rubber bearing supports reinforced with steel plates were used to represent the support [7].

## 4.1. Models Description

Model 1: The dimension of the model is illustrated in Figure (4) and Table (1). The model has four longitudinal reinforcement bars with diameter of 10mm. The stirrups are 6mm in diameter with spacing of 100mm and 20mm in the middle of the height. The properties of the concrete and reinforcement used are shown in Table (2).

Model 2: This model has the same description of Model 1, in addition to carbon fiber sheets (CFS) is used to strengthen the model after collapse. The thickness of (CFS) is 0.111mm, the tensile strength is 3400N/mm2, and the elastic modulus is 245×103 N/mm$^2$.

Model 3: The dimensions of the bridge model are shown in Figure (5), the slab contains four bars of longitudinal reinforcement with a diameter of 10mm.The diameter of the stirrups is 6 mm with a spacing of 150mm, and 250mm in the middle of the height. Young’s modulus is 210kN/mm$^2$, and longitudinal reinforcement strength of 401N/mm$^2$. The bridge slab and the two piers 'models were cast at different dates, thus, after 28 days, the concrete's compressive strength for the beam is 52.2N/mm$^2$, and its elastic modulus is 32.9×103N/mm$^2$. The two piers have a compressive strength of 27.8N/mm$^2$ and an elastic modulus of 26.4 ×103N/mm$^2$.

# 5. Analytical study:

Damping ratio changes with the excitation amplitude were taken from three experimental models that were obtained by conducting free vibration test, Figure (6). The suitable graph of the amplitude-damping ratio relationship of the three models was drawn with correlation coefficient of R2=0.8285 as

2. In modal analysis and in dynamic analysis, as well, the analytical responses result considering the variable damping ratio were closer than the response with variable damping ratio to the experimental response, confirming the necessity of taking the change of the damping during the dynamic analysis.
3. Prior to selecting the design parameters, we must pay close attention to the expected vibration amplitude in order to adopt the dynamic characteristics of any construction.

## 8. Recommendations:

1. Writing a software in an open-source programming language like Python that can be linked with dynamic analysis packages like Abaqus to calculate the dynamic characteristics changes with changes in vibration amplitudes based on the equations given in this research.
2. Performing more experimental models to get more exact relationship of the changing of the damping ration with the amplitude changes.

**Figure (1) RC bridge pier [6]**


(a) Resin epoxy injecting (b) CFS jacket

**Figure (2) RC Bridge pier after strengthen [8]**

lytical natural frequency was found and compare with experimental values. From Fourier spectrum graph that shown in Figure (12) and Figure (13), the first natural vibration mode was just observed. The experimental and analytical natural frequency values of 10.9Hz and 10.938Hz, respectively, were approximately identical. At the maximum acceleration amplitude of (1.307m/sec$^2$) for the first model, the time history of the analytical acceleration response with a constant damping ratio $\zeta = 0.05$ was compared with the experimental response. Comparatively, Figure (14) shows that the relative difference was 0.709. For variable damping ratio, the variable damping was input against the values of the natural frequency at each time step $\Delta t = 0.023$, which was produced from the analytical solution. The experimental maximum amplitude was compared with the analytical acceleration response, the Figure (15) reveals the relative difference to be 0. 3608.Thus, it is noticed that the mathematical values are fairly closer to the empirical values, in the case of variable damping ratio.

### 6.2.2. Forced vibration:

In this step, the effect of variable damping ratio on the dynamic response was investigated by applying forced vibration analysis. To stay in elastic stage, 15% of Kushiro earthquake record in 1994, Figure (16), was applied. After that the analytical dynamic response of the first model was conducted in the two aforementioned scenarios. The comparison of the experimental response with the analytical response for constant damping is shown in Figure (17). It is obvious from the figure that the relative difference for this comparison was 0.289. Otherwise, in the case of variable damping ratio, Figure (18) shows that the maximum analytical response to experimental response was 0.0128.

## 7. Conclusions

An analytical and numerical study was conducted to investigate the effect of amplitude changes on damping ratio in dynamic analysis of a reinforced concrete bridge piers using Abaqus 6.14 program. The modal analysis and dynamic analysis were carried out on a bridge pier model. The analytical responses, after defining the damping changes function in the analytical model was investigated. The results are given as follow:

1. The damping ratio rises as the maximum excitation amplitude increases.

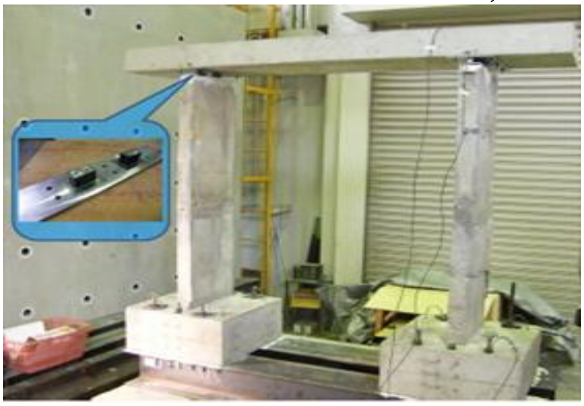


**Figure (3) RC bridge model [7]**

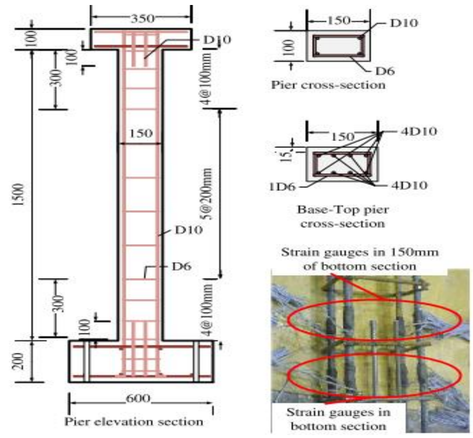



**Figure (4) Geometrical parameters of Model 1 and Model 2[6]**

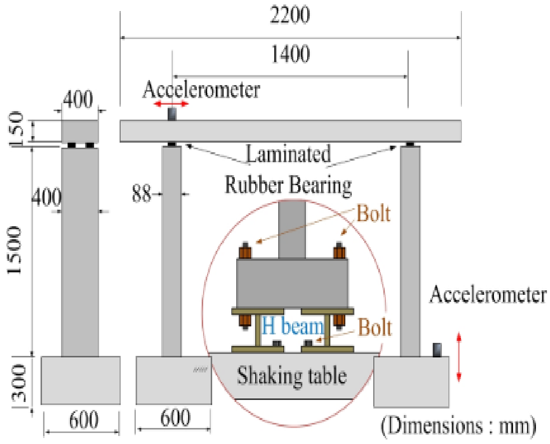



**Figure (5) Geometrical parameters of Model 3 [7].**

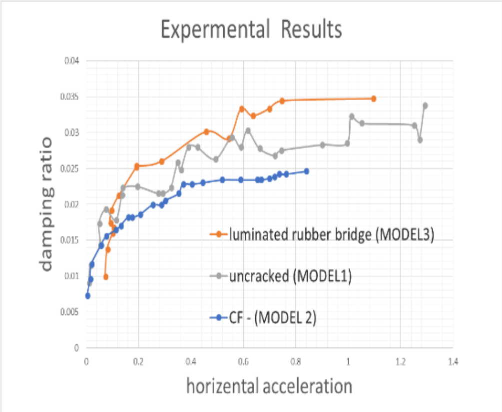



**Figure (6) Experimental damping ratio vs acceleration amplitudes**

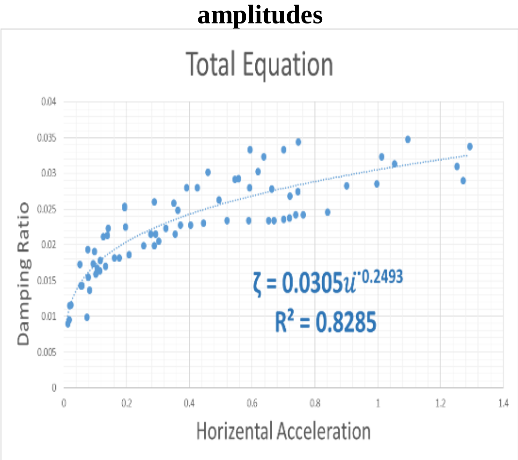



**Figure (7) Three samples' experimental damping ratio vs acceleration amplitudes**

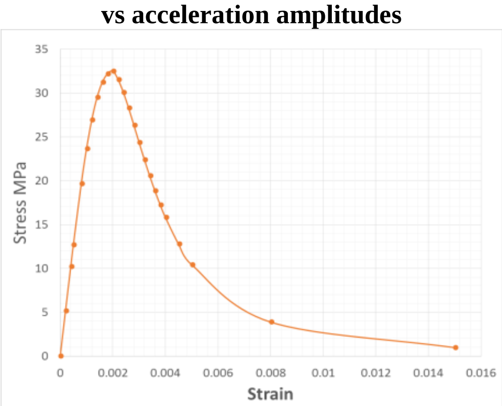
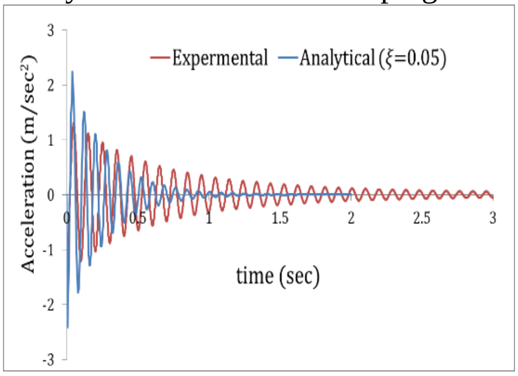



**Figure (8) Stress-strain diagram of concrete**




F Figure (14) Acceleration time history with constant damping ratio (modal analysis)

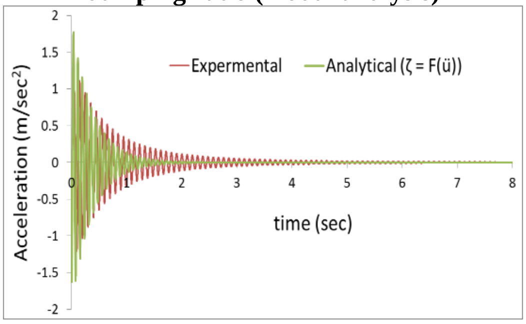



Figure (15) Acceleration time history with variable damping ratio (modal analysis)

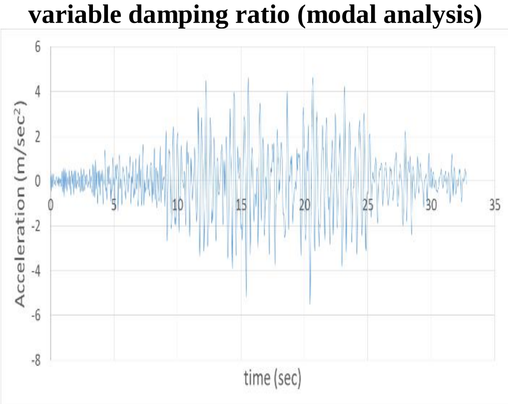



Figure (16) Kushiro earthquake record

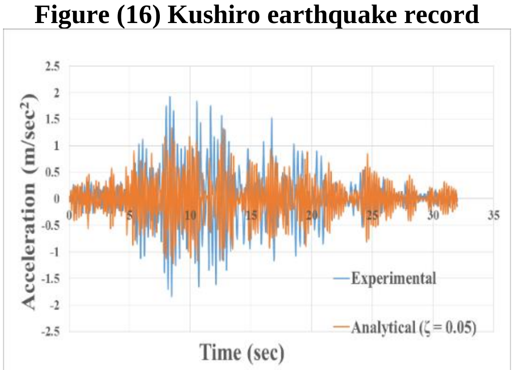



Figure (17) Acceleration time history with constant damping ratio (dynamic analysis)

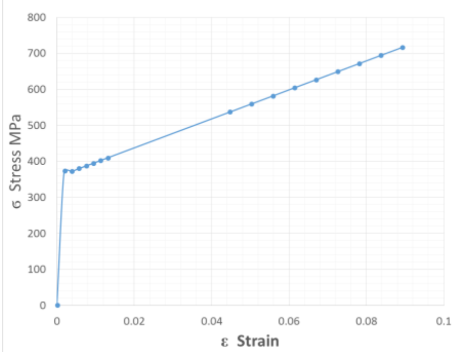



Figure (9) Stress-strain diagram of steel

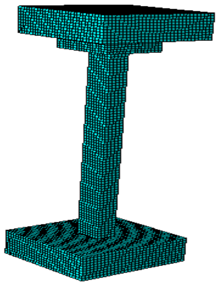


Figure (10) Numerical model of bridge pier

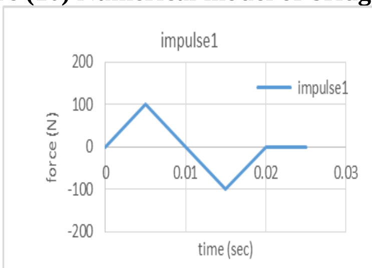



Figure (11) Triangular pulse

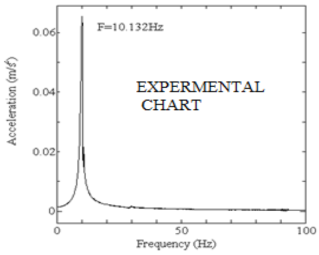



Figure (12) Experimental Fourier spectrum [8]

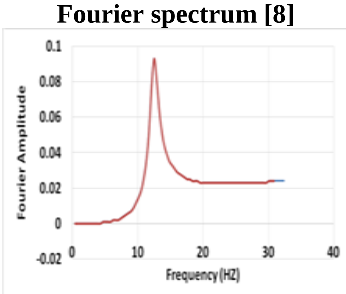



Figure (13) Analytical Fourier spectrum

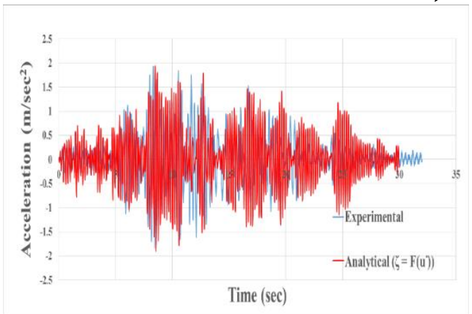



**Figure (18) Acceleration time history with variable damping ratio (dynamic analysis)**

**Table (1) Dimensions of bridge pier models**

| Element | | Cross-section (mm) | Height (mm) |
|---|---|---|---|
| Model (1), (2) | Column | 100×500 | 1500 |
| | Cap | 300×350 | 100 |
| | Concrete block | 600×600 | 200 |
| Model (3) | Column | 88*400 | 1500 |
| | Concrete block | 2200*400 | 150 |
| | foundation | 600*600 | 300 |

**Table (2) concrete and steel properties**

| | Elasticity modulus | Poisson ratio | Compressive strength |
|---|---|---|---|
| unite | Mpa | – | Mpa |
| concrete | 29100 | 0.18 | 32.5 |
| steel | 210000 | 0.3 | 401 |

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