投稿論文（英文ノート）

TECHNICAL NOTE

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ON HIGH-FREQUENCY SEISMIC MOTIONS OF REINFORCED CONCRETE STRUCTURES

Masayasu OHTSU[1]

[1]Member of JSCE, Dr. of Eng., Professor, Dept. of Civil and Environmental Eng., Kumamoto University
(Kurokami 2-39-1, Kumamoto 860, Japan)

In relation to disastrous damage of reinforced concrete (RC) columns due to recent Hanshin-Awaji Earthquake, high-frequency behavior of RC beams subjected to impact loading is reexamined. Thus, the effect of high-frequency horizontal motions on the columns is inclusively studied, solving RC beams in the elastic range by BEM. From the dimensional analysis, it is suggested that the local failure mode of the columns due to horizontal motions could result from high-frequency earthquakes over 10 Hz. The stress analysis suggests spalling failure of cover concrete due to high-frequency bending motions and the high shear stress zone localized at one end due to the higher frequency motions.

Key Words : *impact test, RC members, BEM analysis, dimensional analysis, high-frequency motion*

1. INTRODUCTION

Recent Hanshin-Awaji Earthquake has brought tremendous disaster and damage on concrete structures[1)]. As a result, numerous topical issues and urgent forums are offered by a variety of organizations, institutes and societies. One of unexpected disaster widely-reported is failure and damage of reinforced concrete (RC) columns. Some of critical phases on the failure are pointed out, as follow :

1) causal directions of vibration ; horizontal or vertical,
2) failure modes resulted in disastrous failure ; shear or bending, and
3) effect of high-frequency motions due to epicentral quake.

At present, answers and reasons on these findings are intensively studied by a number of research groups. Previously, dynamic behavior of RC beams due to impact was investigated in our lab., and some effects of high-frequency motions on the beams were clarified by the boundary element method (BEM)[2)]. Reexamining these results and analyzing new models, the effect of high-frequency horizontal motions on the RC column is studied. The effect of high-frequency motions on RC members is not probably associated with ultimate failure, but could be referred to as triggering the nucleation of dynamic failure. Consequently, the analysis is conducted on RC beams in the elastic range. Although the boundary conditions of the columns are different from those of the beams, the basic relation between the resonance modes of high-frequency motions and the failure modes could be derived from the dimensional analysis. In order to clarify the stress generation under dynamic motions, the elastic stress analysis of RC beams due to high-frequency loads is also performed.

2. DYNAMIC MOTIONS

Dynamic elastic behavior of a RC member is mathematically represented by a function, $F(\boldsymbol{x}, t)$ on the location vector, $\boldsymbol{x}$ and time variable, t. Since a continuous function on t can be expanded into Fourier series, we have,

$$F(\boldsymbol{x}, t)=\sum[a_n(\boldsymbol{x})\cos 2\pi f_n t+b_n(\boldsymbol{x})\sin 2\pi f_n t)]$$
$$=\sum c_n(\boldsymbol{x})\exp(i2\pi f_n t). \qquad (1)$$

Complex coefficient $c_n(\boldsymbol{x})$ at frequency f_n can be obtained as solution $u_i(\boldsymbol{x})$ of Navier's equation in the steady state,

$$(\lambda+\mu)u_{j,ij}(\boldsymbol{x})+\mu u_{i,jj}(\boldsymbol{x})+(2\pi f_n)^2 u_i(\boldsymbol{x})=0, \qquad (2)$$

where λ and μ are Lame constants.

From eqs. 1 and 2, it is realized that actual behavior of the structure could be reproduced as a linear combination of the motions $u_i(\boldsymbol{x})$ at particular frequency f_n. Thus, a key issue is the analysis of dynamic steady-motions due to particular frequency incidence. For this purpose, a BEM code for the two-dimensional (in-plane motion) elastodynamic steady-state problem is developed[2)].

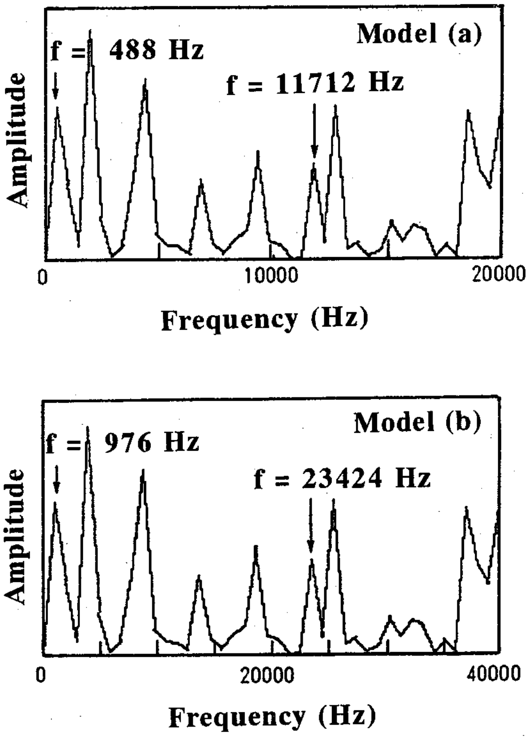


Fig. 1 Frequency responses of the two RC beams.

3. DIMENSIONAL ANALYSIS

Dynamic behavior of a structure is characterized by incident wave motions, material properties, and structure sizes. The kinetics of motions is prescribed by frequency f, or period T which is equal to $1/f$. The material property essentially responsible for dynamic motions is elastic-wave velocity v, which is derived from Young's modulus, Poisson's ratio, and the density. The effect of the kinetics and the wave velocity are united as wavelengths, v/f. Then, a relation between the wavelength and the structure sizes contributes to complicated dynamic behavior of the structure.

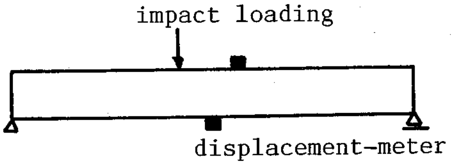
In the present case, the structure sizes to be taken into account are the length or span L, and the width or depth, h, of the member, which lead to a non-dimensional parameter; aspect ratio λ. Normalized parameter κ is assumed as the following function,

$$\kappa=F(f, v, L, \lambda). \tag{3}$$

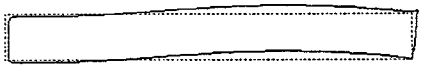
The analysis leads to a relation,

$$\kappa=\lambda f L/v. \tag{4}$$

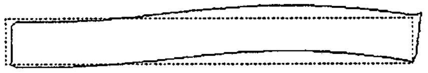
This implies that the similar dynamic behavior is predicted in the case that parameters κ and λ are identical.



(1) Case κ=0.878 (λ=9)

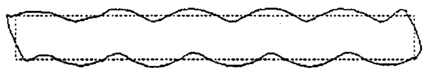


Model (a) at 488 Hz

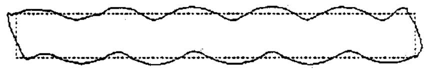


Model (b) at 976 Hz

(2) Case κ=21.08(λ=9)



Model (a) at 11712 Hz



Model (b) at 23424 Hz

Fig. 2 Resonance vibration modes at the two peak frequencies in Fig. 1.

The applicability of the relation is studied by analyzing dynamic responses of two similar RC beams. These are model (a) of dimension L=90 cm and h=10 and model (b) of dimension 45cm×5cm. Both models are of the aspect ratio $\lambda=9$, and are loaded at 2/9 of the span from the left edge. Vertical displacements on the top at 4/9 of the span from the right edge are analyzed by BEM. Configuration of the specimen is given at the top of **Fig. 2**. In the analysis, equivalent Young's modulus to the RC beam is employed[2]. Young's modulus is 34.3 GPa, Poisson's ratio is 0.2, and the density is 2300kg/m^3. Responses due to impact with 488Hz frequency increment are shown in **Fig. 1**. P wave velocity of the models v_p, is identical, because of the same material constants.

From eq. 4, input frequencies f_a of model (a) and f_b of model (b) are related as,

$$\kappa=9f_a(0.9)/v_p$$
$$=9f_b(0.9)/v_p.$$

And thus, $2f_a=f_b$ (5)

The relation of eq. 5 clearly holds in **Fig. 1**. Vibration modes at the two peak frequencies in **Fig. 1** are given in **Fig. 2**. In the model (a), the peak frequency 488Hz corresponds to the case $\kappa=0.878$, and $\kappa=21.08$ at another peak frequency, 11712Hz. Between the models (a) and (b), the similarity on vibration modes is surely confirmed.

Corresponding to the case $\kappa=0.878$, the similar resonance vibration of an actual structure is predicted at frequency 13.55Hz for the case that the length $L=18$m, the width $h=2$m, and P wave velocity 2500m/s. It is reported that many columns destructed in the earthquake are of around 10 to 20m height. As can be seen in **Fig. 2**, in the case $\kappa=0.878$, only 1/3 right portion of the beam is dominantly deformed. It suggests the fact that the failure mode of the column corresponding to the resonance deformation given results from high-frequency components of earthquakes over 10Hz. In the case of stubby columns, the aspect ration λ become smaller than those of slender columns. It suggests that the resonance frequency associated with the failure mode could become even higher.

Another suggestion is derived from eq. 4 in respect to hybrid seismic-loading tests[3),4)]. In those experiments, seismic waves are often extended in the time scale. It leads to lower frequency. Since the structure sizes are also smaller in the model tests except for full-scale testing, the parameter κ becomes eventually small and the effect of high-frequency other than large deformation and cyclic loading may not be simulated.

4. STRESS ANALYSIS

To clarify the failure mechanisms and identify the locations of localized failure, the dynamic stress analysis is performed. RC beam of dimension $L=1.2$m and $h=0.06$m (aspect ratio: $\lambda=20$) is analyzed. One reinforcing bar is embedded at 3 cm cover thickness. In the experiments[2)], it was found that the first resonance of axial strain at the center-bottom is observed at 292Hz. Thus, an equivalent Young's modulus was determined as 35.6 GPa. Poisson's ratio was 0.2, and the density was 2490kg/m^3. Furthermore, the effect of reinforcement on dynamic behavior was studied in the experiment. It is realized that the difference between vibration motions of RC beams and those of plain concrete is inconsequential under global resonance modes.

Impact stress 1 MPa of this frequency was applied to the beam. The corresponding stress distribution is given is **Fig. 3**. Negative values indicate compressive stresses. The normalized parameter $\kappa=1.56$ for 292Hz.

As can be seen, the vibration mode and the stress distribution σ_{xx} are of bending. In the central region,

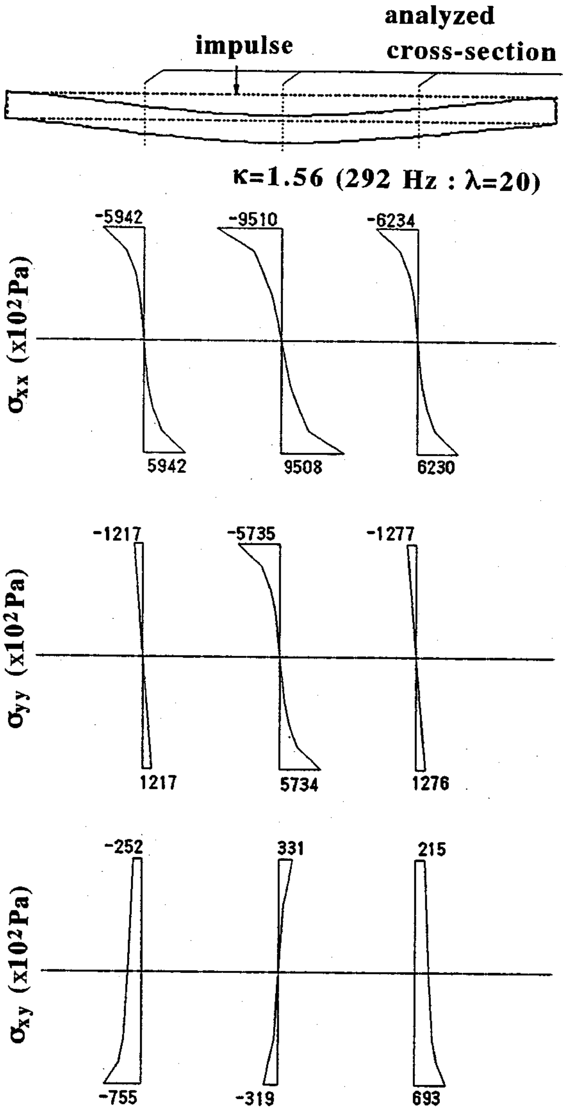


Fig. 3 Stress distribution in the beam at 292Hz ($\kappa=1.56$ and $\lambda=20$).

large tensile stress σ_{yy} almost half of the axial stress σ_{xx} is observed.

Since the axial stress is reinforced in the RC beam, the large σ_{yy} values suggest spalling of cover concrete. In the case that the column length 20m and P wave velocity=2500m/s, an actual frequency corresponds to 9.75Hz. Thus, spalling of cover concrete is predicted due to high-frequency bending motions. It is noted that the ratio of the maximum shear stress to the maximum axial stress is just 8%.

To study the stress distribution of a similar deformation to the case (1) $k=0.878$ in **Fig. 2**, the input frequency 500Hz is applied to the model. The case corresponds to $\kappa/\lambda=0.134$, which is fairly close to the

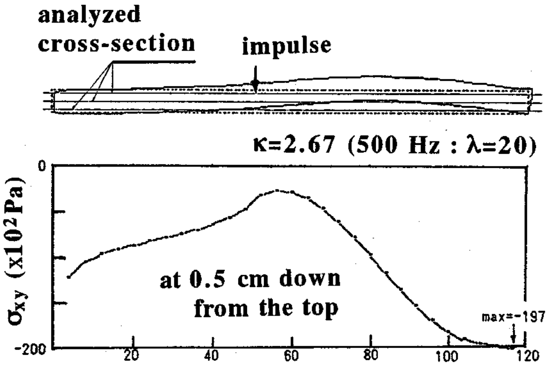


Fig. 4 Shear stress distribution at 500Hz.

case (1) in **Fig. 2** ($x/\lambda=0.098$). A result of shear stress distribution at the cross-section 0.5cm down from the top surface is given in **Fig. 4**. In the analysis, it is found that the maximum axial stress 122kPa. The maximum shear stress is observed −19.7 kPa at nearly the right end of the beam. Since the maximum axial stress was 122 kPa, the ratio of the maximum shear stress to the maximum axial could reach up to 16%, which might be high enough for shear failure. Comparing **Fig. 4** with **Fig. 2**, it is realized that the high shear stress zone is generated at the 1/3 right portion of the beam. It implies that shear failure of the slender column could occur at this region due to high-frequency vibration. Although equivalent Young's modulus is assumed, this is not only the case of plain concrete but also corresponds to that of the RC beam under global resonance modes.

5. CONCLUSION

The effect of high-frequency horizontal motions on the RC column is studied, solving analytically RC beams in the elastic range. The basic relation between the resonance modes of high-frequency motions and the failure modes is elucidated by the dimensional analysis and the elastic stress analysis.

(1) The results of the dimensional analysis suggest the fact that the local failure mode of the column due to horizontal vibration could result from high-frequency components of earthquakes over 10Hz.

(2) Spalling of cover concrete is predicted under high-frequency bending motion. Concerning the local failure mode, the high shear stress zone is identified at the 1/3 right portion of the beam. The stress reaches almost 20% of the maximum axial stress, which may be high enough for shear failure at the end of the column.

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鉄筋コンクリート構造物の地震時高周波数挙動について

大津　政康

阪神・淡路大震災の災害報告により，鉄筋コンクリート（RC）構造物，特に，橋脚の破壊様式が問題となっている．この原因究明にむけて様々な研究が進められているが，本研究ではこれまでに実施した（RC）梁の衝撃試験の結果に基づいて，RC柱の横荷重に対する高周波数挙動の考察を試みたものである．次元解析により，無次元パラメータの実用性を境界要素法のモデル解析により確認した．そして，実在構造物の場合に横振動による共振周波数は10 Hz以上となることが認められた．さらに，応力解析により，高周波数応答時の曲げ振動による剥離ひびわれの発生と高せん断応力領域の発生の可能性を明かにした．

米国ITASCA（イタスカ）社開発の岩盤・地盤解析プログラム

未来設計企業
CRC

UDEC
3DEC

個別要素法（DEM）プログラム

個別要素法（離散要素法）は、1971年にDr.P.Cundallが発表した不連続体数値解析手法であり、岩盤や地盤をブロックや土粒子の要素の集合体と考え、個々の要素が隣接要素から受ける力により運動方程式にもとづき挙動する様子を時間差分式にて時刻繰返し計算する手法です。個別要素法は不連続力学の中心手法として位置づけられ、岩盤・地盤の崩落や安定性の解析、大深度地下空間、核廃棄物地下処理、鉱物資源開発等のプロジェクトおよび粒状体力学（粉体工学）の分野で有力な解析手段となっています。現在UDEC，3DECは全世界の研究機関・企業で標準コードとして広く使用されています。

オプション

■ Barton-Bandisモデル

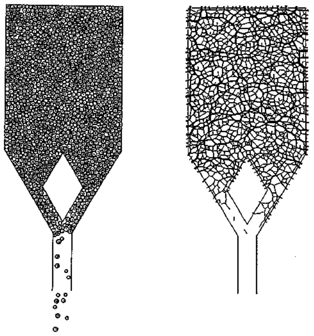
適用分野

- ●粒状物質の挙動解析
- ●鉱山採掘等　掘削解析
- ●地震応答解析
- ●ジョイント内流れ解析
  （浸透連成：UDEC）
- ●核廃棄物の熱応力解析
  （熱連成：UDEC）

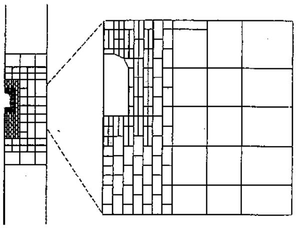
■販売条件

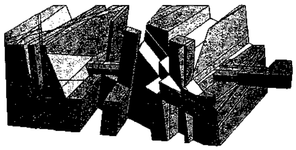
UDEC・3DEC・FLAC

- ◆EWS（SUN-SPARC）
- ◆IBM-PC/AT及び互換機
- ◆UDECはソースコードで提供します。
- ◆3DEC・FLACはロードモジュールで提供します。

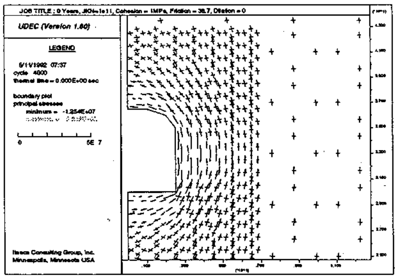


ホッパー内粒状体挙動解析





亀裂性岩盤の3次元掘削解析



核廃棄物地中処理影響解析

FLAC

有限差分法（FDM）プログラム

FLACは個別要素法コードUDEC，3DECを発表したDr.P.Cundallが同様の有限差分ロジックを用いて連続体の塑性大変形の解析するために開発したコードで、現在、全世界で数多く使用されています。有限差分法は、地盤、岩盤を有限な領域内で離散化し、運動方程式と構成則を差分方程式として解析するもので、有限要素法に比べ非線形大歪が扱えることで大きな優位性を持っています。

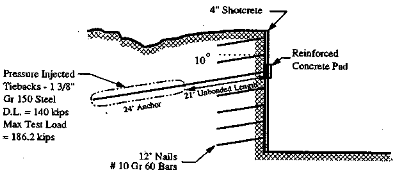
FLACは小ー大歪　非線形、動的ー静動挙動を始めとし、豊富な機能　オプションを備えたPC、ワークステーション用の地盤解析コードです。

オプション

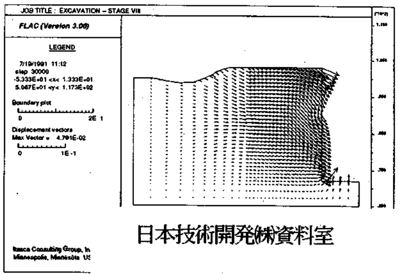
■ダイナミック解析モデル
■クリープ解析モデル
■熱解析モデル

適用分野

- ●斜面・盛土の設計、安定解析
- ●浅／深基礎設計
- ●アースダム、コンクリートダムの設計
- ●トンネルの設計
- ●核廃棄物貯蔵解析
- ●液状化解析



地盤安定解析



株式会社CRC総合研究所

●西日本事業部　科学システ
〒541 大阪市中央区久太郎
●科学システム事業部　営業
〒136 東京都江東区南砂2-

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