三次元的な地下構造を有する堆積盆地の水～土骨格連成弾塑性地震応答解析

Elasto-plastic soil-water coupling seismic response analysis of a sedimentary basin with a three-dimensional geometry

*野田 利弘[1]、豊田 智大[1]、岩井 周平[2]、浅岡 顕[3]
*Toshihiro Noda[1], Tomohiro Toyoda[1], Shuhei Iwai[2], Akira Asaoka[3]

1. 名古屋大学減災連携研究センター、2. 名古屋大学工学研究科、3. 地震予知総合研究振興会
1. Disaster Mitigation Research Center, Nagoya University, 2. Graduate School of Engineering, Nagoya University, 3. Association for the Development of Earthquake Prediction

地盤内部に非一様な堆積構造が存在する場合，地盤内の波動伝播は複雑なものとなることが知られている．とくに堆積盆地においては，堆積層内での加速度増幅や実体波のレンズ効果に加えて，盆地端部において生成された表面波との干渉に伴うエッジ効果により局所的に強い揺れが生じるとともに，長時間に亘り揺れが継続することが知られている．そこで本報では，表-1(d)に示す三次元球形盆地を対象に一相系弾性・二相系（水～土連成）弾塑性地震応答解析を実施し，堆積構造の三次元性および地盤材料の弾塑性および間隙水の存在がその震動特性に及ぼす影響について調べた．

まず，図-1の三次元メッシュ（形状は宮本ら[1]に準拠）に対して一相系弾性解析を実施し，三次元性に起因して生じる複雑な波動伝播を観察した．数値解析には，著者ら名古屋大学地盤力学研究室が開発した地盤変形解析コード***GEOASIA***[2]を用いる．平面ひずみ土槽を想定し，前背面の*y*方向変位を拘束するとともに，左右面には周期境界を課した．底面においては，鉛直変位を固定するとともに，水平方向に粘性境界条件を課し，入力地震動として図-2に示す神戸波のEW成分を*x*方向に入力した．弾性体の材料定数は割愛するが，堆積層と基盤層の間で明瞭な剛性のコントラスト（インピーダンス比で11.4倍）を与えている．得られたせん断ひずみ分布および変位速度場を図-3および図-4に示す．解析初期における円環状のひずみ集中帯の発生に加え，盆地内での波の滞留が確認されたほか，三次元性に起因して，*y*方向および*z*方向の変位速度を生じる様子が解かれた．

次に，三次元盆地の解析解を表-1(a)-(c)の低次元モデルの解と比較することで，三次元性が地表面の揺れに及ぼす影響を定量的に評価することを試みた．盆地中央の堆積層における水平加速度応答を図-5に示す．同図より，いずれの低次元モデルも，三次元モデルに対して最大加速度および地震動の滞留時間を過小評価していることから，簡便な低次元モデルによる応答評価の限界が示唆された．また，堆積層における盆地中央での伝達関数（図-6）より，一次元モデルでは理論解（1/4波長則）に従う増幅特性が得られるのに対し，三次元モデルでは様々な周波数帯における増幅が確認されるなど，一次元解析とは大きく異なる結果となることを示した．

さらに，材料を弾塑性体として，間隙水の存在を考慮可能な水～土骨格連成解析を実施した．弾塑性構成式にはSYS Cam-clay model[3]を用いた．材料定数および初期状態については割愛するが，基盤層は固結の進んだ岩，堆積層は緩い砂地盤をそれぞれ模擬して典型的なパラメータを設定し，神戸波EW成分の振幅を1/10として*x*方向に入力した．解析の結果，図-7のように地震中に有効応力が低下して地盤が液状化し，堆積層全体が図-8のように一様に流動する「スロッシング」のような現象が解かれた．液状化の発生は，図-9に示す地表面の要素挙動においても確認できる．さらに，図-10に示す伝達関数の推移から，液状化に伴って堆積層内での増幅率が1を下回る（波が伝わらなくなる）様子が見てとれる．以上を通して，盆地構造を有する地盤の地震応答評価における水～土連成弾塑性解析の必要性を示した．

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[2] Asaoka, A., Noda, T., Yamada, E., Kaneda, K. and Nakano, M. (2002): An elasto-plastic description of

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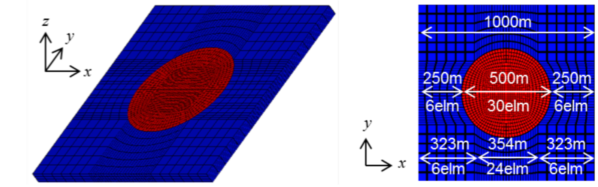
キーワード：堆積盆地、地震応答解析、弾塑性、水～土連成、三次元
Keywords: Sedimentary basin, Seismic response analysis, Elasto-plasticity, Soil-water coupling, Three-dimensional

Table 1. Cases of the numerical simulation

Case	(a)	(b)	(c)	(d)
Model	1D	2D	2D	3D
Shear wave	Considered	Considered	Considered	Considered
Amplification	Considered	Considered	Considered	Considered
Reflection	Considered	Considered	Considered	Considered
Refraction	–	Considered	Considered	Considered
Rayleigh wave	–	Considered	–	Considered
Love wave	–	–	Considered	Considered



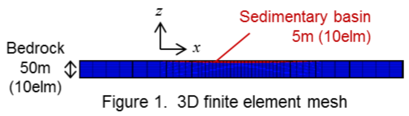


Figure 1. 3D finite element mesh

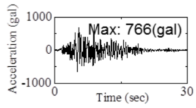


Figure 2. Input wave

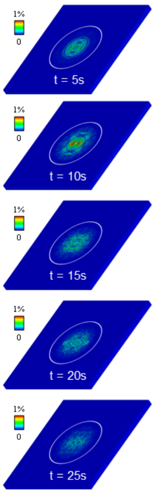


Figure 3. Shear strain (elastic)

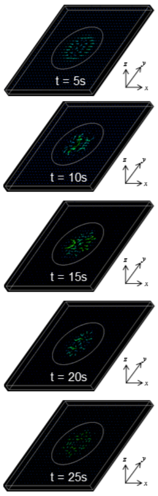


Figure 4. Velocity (elastic)

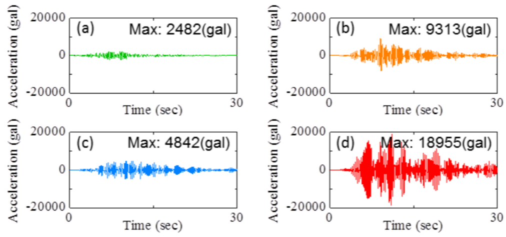


Figure 5 Surface acceleration in x-direction (elastic)

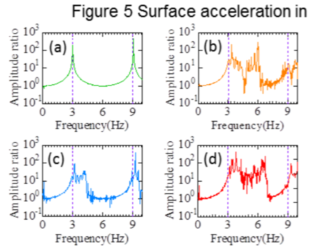


Figure 6 Transfer function of sedimentary basin in x-direction (elastic)

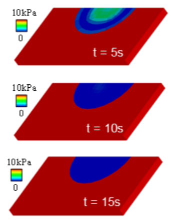


Figure 7. Mean effective stress (elasto-plastic)

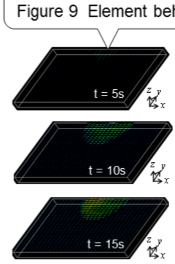


Figure 8. Veloity (elasto-plastic)

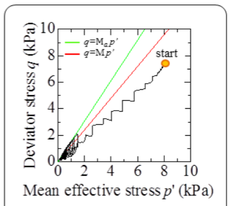


Figure 9 Element behavior

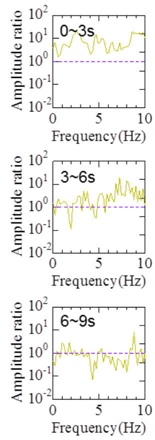


Figure 10. Transfer function (elasto-plastic)

Elasto-plastic soil-water coupling seismic response analysis of a sedimentary basin with a three-dimensional geometry

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1. Disaster Mitigation Research Center, Nagoya University, 2. Graduate School of Engineering, Nagoya University, 3. Association for the Development of Earthquake Prediction

The seismic wave propagation is strongly affected by the ground non-uniformity. Especially in the sedimentary basin, the amplification in the sedimentary layer, the lens effect, and the edge effect due to the interference of the surface wave generated at the edge of the basin cause the strong ground motion. In this abstract, we conducted a single-phase elastic/two-phase (i.e., soil-water coupled) elasto-plastic seismic response analysis for the three-dimensional spherical basin shown in Table 1(d) and investigated the effects of three-dimensional structures, elasto-plasticity, and the presence of pore water.
First, a single-phase elastic analysis was performed on the three-dimensional mesh (conformed to Miyamoto et al.[1]) shown in Fig. 1. The analysis was conducted with the analysis code ***GEOASIA***[2] developed by the authors. Assuming a plane strain shear box test, the displacement of the front and back surfaces in *y*-direction was fixed and the periodic boundary was imposed on the left and right surfaces. At the bottom of the model, the vertical displacement was fixed and the viscous boundary condition was imposed in the horizontal direction. The EW component of the Kobe wave shown in Fig. 2 was applied in the *x*-direction as an input wave. As for the elastic material constants, we considered a clear rigidity contrast (11.4 times in the impedance ratio) between the sedimentary layer and the bedrock. As an analysis result, we confirmed the initial emergence of the ring-shaped strain concentration (Fig. 3), the occurrence of the three-dimensional waves and its long-term retention (Fig. 4).
Next, we compared the three-dimensional result with the reduced-dimensional model shown in Table 1(a)-(c) for evaluating the effect of the three-dimensionality of the sedimentary basin. Figure 5 shows the horizontal response on the ground surface at the center of the basin. As indicated in the figure, all reduced models underestimated the maximum acceleration and the residence time of seismic motion. The result suggests the limitation of the evaluation by the reduced-dimensional model. As for the spectral characteristics, the transfer function of the sedimentary layer at the center of the basin in the three-dimensional case in Fig. 6(d) indicated the amplification in the various frequency range, whereas the one-dimensional calculation in (a) just exhibited the theoretical solution.
Moreover, we conducted the two-phase elasto-plastic analysis. The SYS Cam-clay model [3] was used as the elasto-plastic constitutive equation. The typical parameters for consolidated rock and loose sand were assumed for the bedrock and the sedimentary layer, respectively. The analysis results for 1/10 amplitude of the Kobe wave indicated the decrease of the effective stress (liquefaction) in Fig. 7 and the sloshing behavior of the entire sedimentary layer in Fig. 8. The occurrence of liquefaction could also be confirmed in Fig. 9. Furthermore, the running transfer function in Fig. 10 indicated that the liquefaction reduced the transfer of the shear wave in the sedimentary layer.
(Acknowledgement) Numerical simulations were conducted by utilizing a supercomputer system in Kyoto University, Japan. And we received Grant-in-Aid for Scientific Research (Grant-in-Aid for Scientific Research (A): No. 17H01289).
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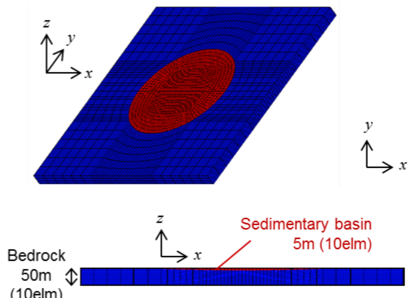
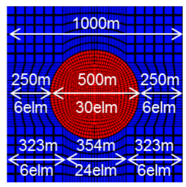

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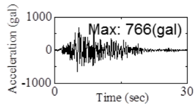

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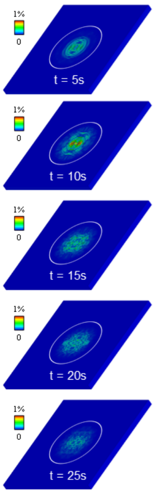
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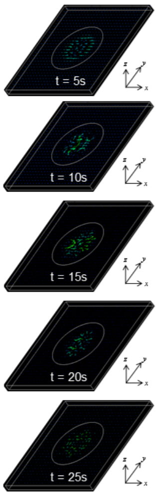
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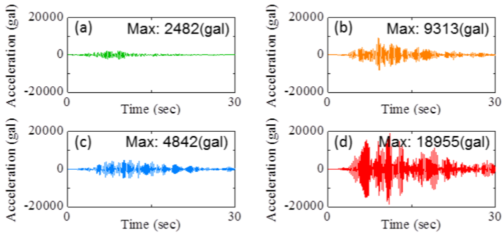

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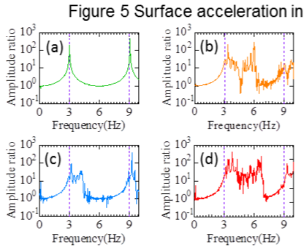
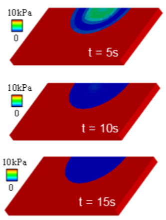


Figure 6 Transfer function of sedimentary basin in x-direction (elastic)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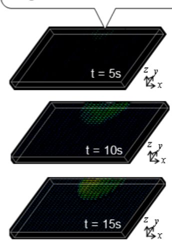
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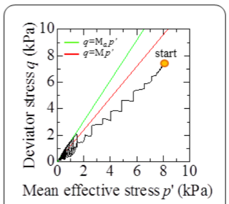

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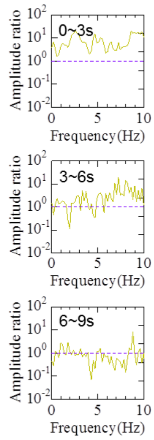

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