砂土液化引起大位移对地下管道影响的非线性分析①

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摘要:地下管线是生命线工程的主要部分,已经成为现代工农业生产和城镇生活的大动脉。已有震害调查表明,饱和砂土液化引起的地基大变形(侧向变形和沉降)是导致强震区生命线工程震害的主要原因。采用三维非线性有限差分分析方法来研究砂土液化引起的大位移对地下管道的破坏特征,分析砂土液化的斜坡变形特征、孔隙水的演化过程。结果表明,砂土液化引起的大位移对地下管道有破坏作用,导致管道变形规律与其斜坡的位移规律相同,地下管线的变形随着振动频率和幅值的增加其非线性增大。

关键词:液化;地下管线;大位移;三维;非线性

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Nonlinear Analysis of Influence of Large Displacement Induced by Sand Liquefaction on Underground Pipeline

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Abstract: Underground pipelines are the big arteries of present-day industry, agriculture, and city life. It is important to ensure the safety of pipelines in operation, especially under seismic loading. For underground pipelines, seismic damages can be classified as either wave-propagation damage or permanent ground-displacement damage. There have been some events where pipe damage has been due only to wave propagation. More typically, pipeline damage is due to a combination of hazards. However, the damage from large ground displacements typically occurs in isolated areas of ground failure and tends to be greater, whereas wave propagation tends to cause less damage. Large liquefaction-induced displacement (lateral displacement and settlement) is a potential source of major damage to underground pipelines during earthquakes. Therefore, soil liquefaction does major damage to underground pipelines during earthquakes. In order to analyze the damage to underground pipelines under a slope due to sand liquefaction, a three-dimensional nonlinear analysis was carried out to study the pipe characteristics damaged by liquefaction-induced large displacements using the FLAC finite-difference method and to analyze the displacement characteristics of the slope due to sand liquefaction and the pore water pressure buildup. A numerical model was established, which is similar to the real engineering project dimensions. The model consists of the saturated sand and dry sand layers, as well as the pipeline buried under the slope. The saturat-

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ed sand on the foundation was modeled using a Mohr-Coulomb soil model coupled with a Finn model, which is the pore water pressure generation model. The dry sand of the slope was also modeled as a Mohr-Coulomb model without the pore water pressure generation model. The soil-pipe interaction was simulated by a bilinear elastic model, in which the elastic modulus before liquefaction is 103 times that after liquefaction. The base boundary was a rigid boundary. The calculation process is divided into two stages of static and dynamic analysis. In the initial static analysis, in order to compute the gravity stresses, the base boundary was fixed both horizontally and vertically, and the side boundaries were only fixed horizontally. In the dynamic analysis, free-field boundaries were used, and the sine waves were applied to the base boundary. After computing the static stress conditions, a time history dynamic analysis was carried out for sine wave velocities with different frequencies and amplitudes. It was shown that the occurrence of sand liquefaction and large displacement was caused by large sine waves. The displacement of the slope increased with time, which was different in the various parts of the slope. The displacement below the toe of the slope was bigger than that below the crest of the slope, and the sand above the slope had a trend of slipping into the foot of the foundation. The displacement of the pipe increased linearly in the first stage, and then increased nonlinearly with the increase in damage. The liquefaction-induced large displacement does damage to the buried pipe; the displacement of the pipe increases with an increase in the amplitude and frequency of applied sine waves. It is possible to use the nonlinear method to simulate the soil-structure interaction. It is necessary to find a simplified analysis method for predicting pipe damage.

Key words: liquefaction; underground pipeline; large displacement; three-dimension; nonlinear

0　引言

地下管线是生命线工程的主要部分,如通信、天然气、城市供水、上下水道系统、农业灌溉和石油运输等,已经成为现代工农业生产和城镇生活的大动脉。近年来的大地震中,管线破坏引起了人们越来越多的注意,如日本 1993 年的 Nansei—Old 地震[1]、1993 年 Kushim—Oki 地震和 1994 年 Hokkaido—Toho—Oki 地震[2]。地震中由于供水管线的破坏引起城市缺水,进而导致火灾等次生灾害发生,使得整个城市的基本生活瘫痪。已有震害调查表明[3],饱和砂土地层液化引起的地基大变形(侧向变形和沉降)是导致强震区生命线工程震害的主要原因。

对地下管线抗震方面的研究,大多偏重于地震直接作用(如地震波和断层错动)方面,很少研究地震间接作用(如滑坡、砂土液化和不均匀沉降等)方面。管道的破损一般与管周土变形有关。以往的研究中很少考虑地震时地下管道周边土的变形,特别是液化引起的地面侧向大变形的影响,忽视了土与管道之间的相互作用。目前对于液化地基生命线工程的破坏研究得比较少,特别是对液化引起的地面大变形对生命线工程的破坏。

Miyajima M.[4] 和 Kalliontzis C.等[5] 用静力分析方法来分析地下管道特征。徐凤萍[6]、Takada S.等[7] 和 Prashar Y.等[8] 采用有限元法分析土体液化造成地面大位移时地下管线的内力和变形。吴懿等[9] 运用可靠度理论分析地震液化引起地面大位移对地下管线的影响。

目前已经开展砂土液化引起大变形的三维化研究[10],但国内外对液化引起的大变形对地下管道破坏的机理研究还不深入。本文应用非线性有效应力方法分析砂土液化对地下管线的影响,分析管线破坏的变形特征。

1　三维动态分析

砂土液化地基中地下管线的稳定性问题属于三维问题,使用 Flac 软件,利用有限差分格式和有效应力方法对埋于液化的斜坡地基中地下管线进行三维大变形非线性分析,考虑到网格尺寸和边界条件对计算结果有影响,采用大的斜坡模型进行计算,网格划分见图 1。地基模型由两部分组成,下部为 40 m 厚的饱和砂,上部为 20 m 厚的干砂。静水位在饱和砂

的表面。斜坡水平尺寸和垂直尺寸比例为1∶2。

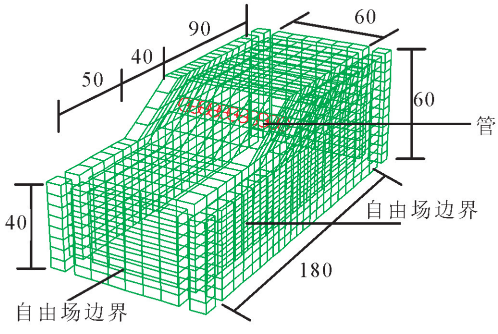

图 1 数值网格划分和模型边界(单位:m)

Fig.1 Numerical mesh and boundary of the model (unit:m)

饱和砂用Mohr-Coulomb与Finn模型(孔隙水压力增长模型)耦合分析,干砂使用Mohr-Coulomb模型分析,模型参数见表1 。

表 1 数值模型的基本参数

Table 1 Basic parameters of the numerical model

土层	土的类型	总密度/(kg·m^{-3})	摩擦角/(°)	剪切模量/kPa	体积模量/kPa	渗透系数/(m·s^{-1})
1	干砂	1 600	36	1.5e+04	2.40e+04	-
2	饱和砂	1 900	35	2.00e+04	3.00e+04	1 e−10

管道在坡顶下埋深10 m,使用结构的梁单元进行模拟,与周边的土关系采用剪切和法向弹簧模拟。管的弹性模量为1.2×10^8 kPa,泊松比为0.25,密度为7 000 kg/m^3,直径为300 mm。土与管之间的关系为双线性弹性关系,见图2。液化前弹性模量为3×10^4 kPa ,液化后模量为30 kPa,采用0.5% Raleigh阻尼。

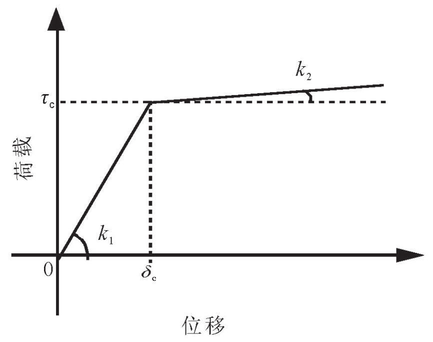

图 2 土与管的双线性关系

Fig.2 Bilinear relationship between soil and pipe

地基边界分两步设置,初始应力分析时底部边界的水平和垂直方向固定;侧面边界在水平方向上固定,垂直方向不固定;在动态分析时侧边界使用自由场边界(Free-field boundaries),使波的反射最小化,底部不是固定边界,利于加水平荷载。

2 动态分析结果

首先进行初始静态应力条件分析,然后进行动态时程分析,水平荷载为多频率和多幅值的正弦波。

2.1 位移和孔隙水压力

本文采用的荷载为速度0.5 m/s、频率5 Hz的正弦波。图3为该荷载加载后的斜坡位移向量。可以看出斜坡上部和基础发生沉降,斜坡下部和坡脚与左侧之间的区域向上发生运动。

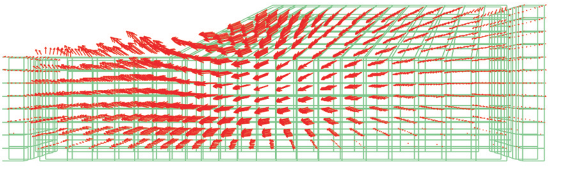

图 3 速度为0.5 m/s,频率为5 Hz的正弦波加载后振动10 s时的位移向量图

Fig.3 Displacement vectors diagram at 10 seconds after vibration under the load of a sine wave with velocity =0.5 m/s, frequency=5 Hz

图4是坡脚和坡顶位置距离地表面10 m深的位移与时间关系图。从图中可见,位移随时间的增加呈非线性增长,5 s前位移变化速率较快,5 s后位移变化放缓,并且坡脚下的位移明显大于坡顶下的位移,说明边坡坡脚在地震砂土液化过程中稳定性急剧降低。这一现象进一步解释了管道不能埋设在坡脚下的理由。

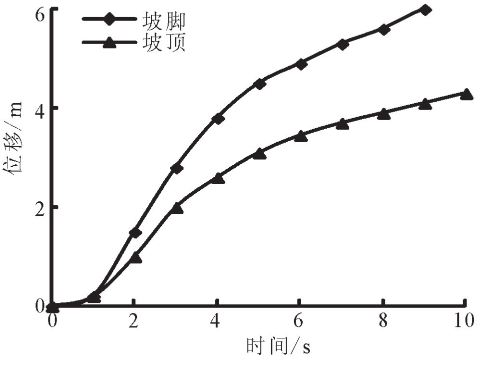

图 4 速度为0.5 m/s,频率为5 Hz的正弦波加载后坡脚和坡顶位置距离地表面10 m深的位移与时间关系图

Fig.4 Displacement vs time of the toe and crest of the slope at a depth of 10 m below the surface under the load of a sine wave with amplitude=0.5 m/s, f=5 Hz

图5是最大孔隙水压力时程曲线图。初期孔隙

水压力随着时间的增加而增长，当达到最大值时砂土发生液化，然后孔隙水慢慢消散，孔压慢慢降低，最后基本趋于稳定。在同一深度，坡顶下的最大孔压值大于坡脚下的值，这是因为砂土液化时重力和动应力不再由土骨架承担，而是由水来承担，即孔压升高，坡顶位置的地基上覆重力大于坡脚位置的上覆重力，所以孔压会大于后者。

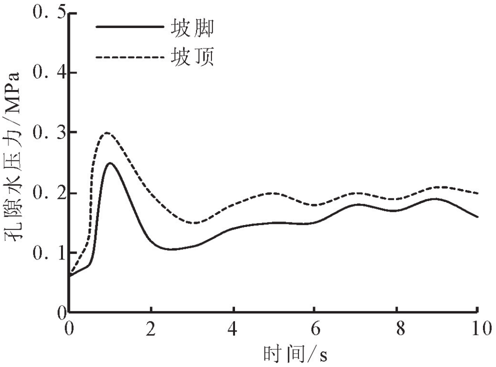

图 5　速度为 0.5 m/s，频率为 5 Hz 的正弦波时坡脚和坡顶下距离地表面 10 m 深度的最大孔压时程图

Fig.5　Maximum pore water pressure versus time of the toe and crest of the slope at a depth of 10 m below the surface under the load of a sine wave with amplitude =0.5 m/s, f=5 Hz

2.2　管的动态反应

地面变形引起的管位移随着振动时间的增加而增大。图 6 是管道中间节点的水平和垂直位移。管道的位移随着时间的增加而非线性地增长，在变形的初期阶段，管的垂直方向略微地向上移动，但随着时间增加位移快速增长，当 5 s 后位移变化缓慢，尤其是垂直位移基本稳定，而水平位移变化速度明显比前阶段小。说明砂土的液化产生的大位移对管道的影响巨大，管道随着土体的非线性位移而相应发生非线性位移，变化规律基本一致。

2.3　动力荷载对管道位移的影响

为考察动力荷载的幅值和速度频率对管道位移的影响，分别进行多频率和多速度幅值的多工况计算。工况分为两类：一类是正弦波频率为 5 Hz，幅值分别为 0.5、1、2、3、4 及 5 m/s；二类是正弦波幅值为 1 m/s，频率为 0.5、1、2、3、4 及 5 Hz 的计算。

图 7 是正弦波为 5 Hz 时波的幅值与管的位移的关系图。图 8 是正弦波幅值为 1 m/s 时，管的位移和速度频率的关系图。管的位移随着幅值和频率的增加而非线性增加，在幅值和频率小的阶段位移增长较快，而在幅值和频率大的阶段位移增长缓慢。

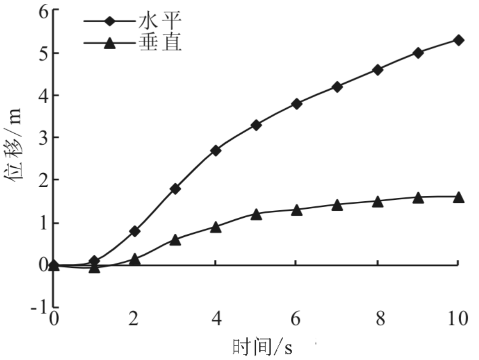

图 6　速度为 0.5 m/s，频率为 5 Hz 的正弦波时管中部位移

Fig.6　Displacement in the middle of pipe versus time under the load of a sine wave with amplitude=0.5 m/s, f=5 Hz

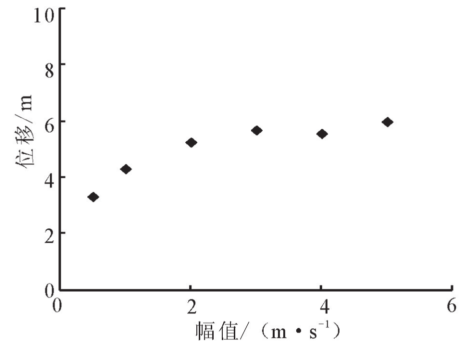

图 7　频率为 0.5 Hz 的正弦波振动 10 s 时管节点位移速度幅值关系图

Fig.7　Displacement of pipe versus velocity amplitude at 10 s after vibration under the load of a sine wave with of f=0.5 Hz

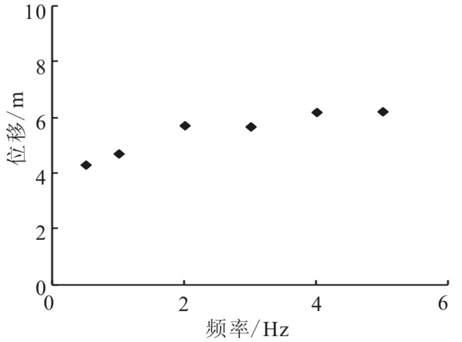

图 8　速度幅值为 1.0 m/s 的正弦波振动 10 s 时管节点位移与速度频率关系图

Fig.8　Displacement of pipe versus velocity frequency at 10 s after vibration under the load of a sine wave with A=1.0 m/s

3 结论

本文对斜坡砂土液化地基的地下管线进行三维非线性有效应力大变形分析，发现液化会引起砂土斜坡产生大的位移，并对地下管线有巨大影响，地下管线的位移随着时间的增加而增长，发展规律与斜坡变形的非线性规律相一致，地下管线的变形随着频率和振幅的增大而非线性增大。使用非线性方法模拟土与管的共同作用是有效可行的。

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