

Tide-induced Air Pressure Fluctuation in Coastal Unsaturated Zones

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Abstract: Air pressure in coastal unsaturated aquifers fluctuates with sea tides, as does the groundwater level. Tide-induced air pressure fluctuations in coastal subsurface systems, however, are not well addressed in literature. Significant diurnal air pressure fluctuations are observed below the asphalt pavement in a coastal reclamation area of Hong Kong. A two-dimensional cross-sectional model is built to describe the air-water two-phase flow in the unsaturated zone of the area. TOUGH2, a general-purpose numerical simulation program for multi-dimensional fluid and heat flows of multiphase, multicomponent fluid mixtures in porous and fracture media, is used to obtain the numerical solutions. The numerical simulation reveals that the significant air pressure fluctuation results from a combination of various factors such as asphalt pavement of extremely low permeability, soil structures of the reclamation area, and rainfall intensity during spring tides. Numerical simulation also reveals that the air pressure is approximately proportional to the tidal rate. A great amplitude of the sea level fluctuation will not necessarily lead to high air pressure, if the sea level changes slowly. Coastal unsaturated zones inhale and exhale as the tidal level falls and rises. The paper goes on to discuss various engineering and environmental implications of air pressure fluctuations in coastal aquifers.

Keywords: air-water two-phase flow, TOUGH2, sea tide, coastal aquifer system, air pressure fluctuation

1 Introduction

While it is well known that groundwater in coastal areas fluctuates frequently due to tidal seawater (e.g., Ferris, 1951; Serfes, 1991; Jiao and Tang, 1999; Li *et al.*, 2002), it is not so well recognized that air pressure in the subsurface soil near the coast may also fluctuate in response to sea tides. If the soil is well capped by low-permeability materials such as concrete or asphalt, which is common in the extensively urbanized coastal areas such as Hong Kong, a significantly high air pressure may be produced by the watertable fluctuation and causes geotechnical problems such as surface heave.

To the best knowledge of the authors, there is little study on the subsurface air flow driven by the fluctuating watertable. Significant air pressure fluctuations have been observed below the asphalt ways in a coastal reclamation area of Hong Kong and caused some concern since the air pressure fluctuation has the potential to cause heave damage to the asphalt way (Geotechnical Consulting Group (Asia) LTD, 2001). In this paper, the mechanism to produce significant air-pressure under the asphalt way will be explored. An isothermal, two-dimensional cross-section model will be built to describe the air-water two-phase flow caused by the sea tide and rainfall infiltration in the unsaturated zone under the asphalt way. TOUGH2 (Pruess *et al.*, 1999) will be used to obtain the numerical solutions of the mathematical model. Some key model parameters will be calibrated against the observed tidal level, tidal rate, and air pressure. It is believed that understanding airflow induced by tidal fluctuation is of not only theoretical interests but also practical significance. Some potential environmental and engineering implications of the air pressure in the unsaturated zone will be briefly discussed.

2 Numerical Study on Tide-induced Air Pressure in A Coastal Area in HongKong

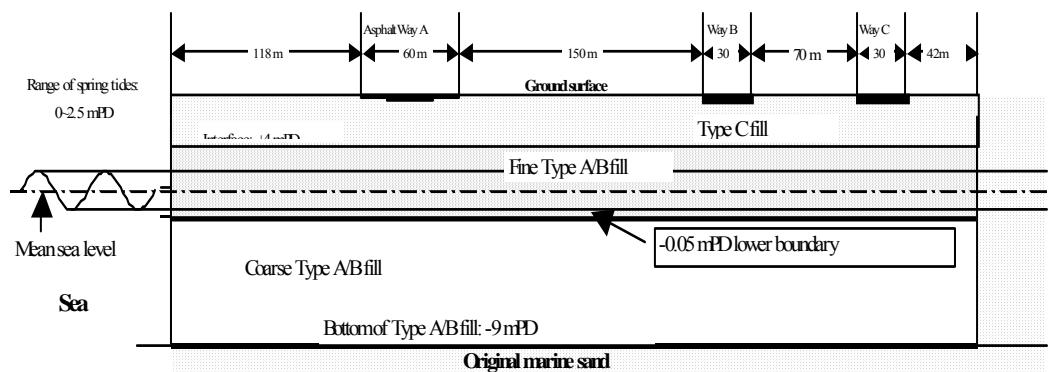


Fig. 1 Cross-section of a coastal reclamation area in Hong Kong

A cross-section of the coastal area formed from land reclamation in Hong Kong is considered in this paper (Fig. 1). There are different materials in the cross-section: the asphalt pavements of the Asphalt Ways A, B and C, the Type C fill below the Asphalt Ways, the fine and coarse Type A/B

fills below the Type C fill. The domain to be studied is a 500 m long and 7.35 m high rectangular area in the cross-section. The left boundary of the rectangle is the water-land interface. The upper boundary is the ground surface, which has an elevation of 7.30 mPD and is covered by either Type C fill or asphalt pavements. The lower boundary is the interface of the fine and coarse Type A/B fills, which has an elevation of -0.05 mPD. The asphalt pavement has the lowest permeability among the fill materials and its permeability has a typical order of magnitude of 10^{-13} m^2 . The Type C fill is much more permeable than the asphalt pavement and its permeability has order of magnitude of 10^{-12} m^2 . The fine Type A/B fill is much more permeable than the Type C fill. Parameters used in the model are presented in Table 1.

2.1 Mathematical model

The mathematical model describing the air-water two-phase flow is based on the mass conservation law with respect to the air and water components. The mass balance equation under isothermal condition can be written in the following general form (Pruess *et al.*, 1999),

$$\frac{d}{dt} \int_{V_n} M^\kappa dV_n = \int_{\Gamma_n} F^\kappa \cdot n d\Gamma_n + \int_{V_n} q^\kappa dV_n. \quad (1)$$

The integration is over an arbitrary subdomain V_n of the flow system under study, which is bounded by the closed surface Γ_n . The quantity M appearing in the accumulation term represents mass per volume, with the superscript $\kappa = a$ for the air component and $\kappa = w$ for the water component. F denotes mass flux. q denotes sinks and sources, which will be used to simulate rainfall infiltrations or to implement time-dependent Dirichlet boundary conditions (Pruess *et al.*, 1999). n is a normal vector on surface element $d\Gamma_n$, pointing inward into V_n .

Table 1 Values of model parameters used in the numerical simulation

| Symbol | Definition | Value |
|----------|--|-----------------------------------|
| ϕ_3 | Porosity of the fine Type A/B fill | 0.3 |
| k_1 | Absolute permeability of the asphalt pavement | $5.6 \times 10^{-14} \text{ m}^2$ |
| S_{h3} | Liquid residual saturation of the fine Type A/B fill | 0.2 |
| k_3 | Absolute permeability of the fine Type A/B fill | $8 \times 10^{-11} \text{ m}^2$ |
| k_2 | Absolute permeability of the Type C marine sand | $5 \times 10^{-12} \text{ m}^2$ |
| ϕ_1 | Porosity of the asphalt pavement | 0.08 |
| ϕ_2 | Porosity of the Type C marine sand | 0.3 |
| S_{h1} | Liquid residual saturation of the asphalt pavement | 0.3 |
| S_{h2} | Liquid residual saturation of the Type C marine sand | 0.5 |

2.2 Numerical method and model discretization

The numerical solutions of the air-water two-phase flow in the rectangular domain are obtained using the EOS3 module in TOUGH2. The discretization of the mathematical model results in a set of strongly coupled nonlinear algebraic equations, with the time-dependent primary pressure and saturation variables of all grid blocks as unknowns. A Cartesian (rectilinear) mesh is used for the numerical simulation. The domain is divided into $39(\text{horizontal}) \times 91(\text{vertical}) = 3549$ sub-rectangles.

The simulation period is 72 hours from February 7 to 9, 2001.

2.3 Simulation results

Fig. 2 shows the observed and simulated air pressures immediately below the Asphalt Way A and the observed tidal rate during the 72-hour period from February 7 to 9, 2001. The observed and simulated air pressures match well.

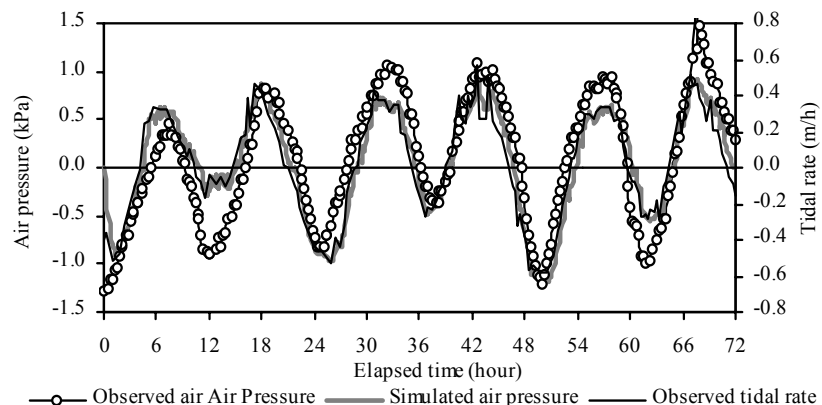


Fig. 2 Observed and simulated air pressures and observed tidal rate

The times when the maximums and minimums of the observed air pressure occur are very close to those of the simulated air pressure.

Fig. 2 also shows that the simulated air pressure is approximately proportional to the tidal rate. The times when the air pressure reaches its maximums and minimums are in line with the times when the tidal rate reaches its maximums and minimums, respectively. This is an important conclusion. It implies that the maximum air-pressure is determined by the maximum rising speed, but not by the variation amplitude, of the sea level. A great amplitude of the sea level fluctuation will not necessarily lead to high air pressure, if the sea level increases slowly. On the other hand, a sudden rise of the sea level will induce high air pressure, although the amplitude of the sea level fluctuation may not be great.

Fig. 3 presents the velocity distributions of the simulated air flow in the unsaturated zone when time equals 18.6 and 25 h at which the air pressure reaches its maximum and minimum, respectively. The following observations can be made from the figure. (a) Due to the great areal extent of the Type C fill of low permeability around the Asphalt Way A, the airflow below the Asphalt Way A is almost symmetric with respect to its vertical middle line. (b) Air flows below the asphalt pavements are almost horizontal. This is because the air permeability of the asphalt is several orders of magnitude smaller than those of the other fill materials and there is almost no airflow through the asphalt pavements. In places that are not capped by asphalt pavements, vertical airflow becomes dominant. (c) When time equals 18.6 h, the tidal rate approximately reaches its maximum (Fig. 3(A)).

The rise of the watertable, which is assumed to be the same as the sea level, compresses the air above the watertable and induces the increase of air pressure. As a result, the ground surface exhales, which is clearly indicated by the airflow velocity field in Fig. 3(B). When the rising speed of the watertable reaches its maximum, the air pressure reaches its peak. When the time equals 25 h, the tide approximately reaches its maximum falling rate. The fall of the watertable leaves extra pore space in the subsoil above the watertable and induces the decrease of air pressure. The ground surface then inhales, as clearly indicated by the airflow velocity field in Fig. 3(B). When the falling speed of the watertable reaches its maximum, the air pressure reaches its minimum.

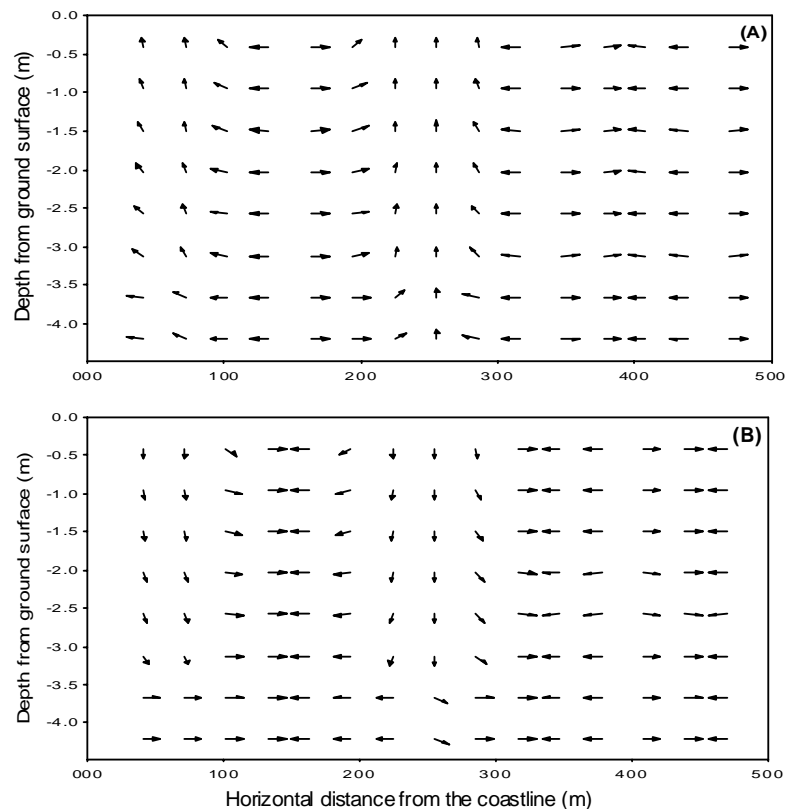


Fig. 3 Velocity distributions: unsaturated zone exhales (A) and inhales (B) when tidal level falls and rises

3 Environmental and Engineering Implications

It is speculated that understanding airflow induced by tidal fluctuation may be of not only theoretical interests but also practical significance. The cyclic fluctuation of the air pressure in coastal unsaturated zones may have both positive and negative implications in coastal environment and engineering and therefore deserves further investigation.

3.1 Rainfall infiltration

Air pressure fluctuation may have an impact on rainfall infiltration in coastal aquifers. As rainfall continues, the wetting front will move down. Due to oscillatory flow of air, the wetting

front is pulled downwards and pushed upwards when the pressure decreases and increases. The net effect may not be nil. When the wetting front moves down and the soil becomes wet, the unsaturated hydraulic conductivity is increased, which will enhance infiltration in the next cycle. In this sense, the wetting process in unsaturated soil is irreversible. Therefore, it is believed that air pressure fluctuation will generally increase rainfall infiltration, especially at the initial stage of the infiltration process.

3.2 Contaminant transport and bioventing process

Air fluctuations in the coastal shallow soils may cause the vertical diffusivity of contaminants in an otherwise stagnant aquifer to be as much as an order of magnitude larger than would occur by molecular diffusion alone. Consequently the contaminants in the vadose zone can move downwards much faster in coastal areas effected by tides than otherwise.

On the other hand, the air pressure fluctuation induced by tides may have positive effect on respiration rate for bioventing process in aquifer remedialtion. Bioventing is a process designed to provide indigenous organisms with adequate oxygen to aerobically degrade target contaminants. Such a system is usually very expensive since continuous injection of oxygen or fresh air into the contaminated soil is required. Bioventing by taking advantages of natural vadose zone air exchange caused by air pressure fluctuations induced by tides may be less expensive.

3.3 Effect of cyclic pressure loading on coastal structure

Coastal areas are usually highly urbanized. Ground surfaces are well capped with concrete and asphalt materials as a result of construction of various structures such as buildings, highways, container ports, and airports. Conventionally, the materials are designed only to support certain loading acting downwards onto the surface. Because of the fluctuation of air pressure induced by tidies, there is cyclic pressure acting upwards from beneath the ground surface. Since engineers may not be aware of the existence of such a cyclic pressure, the effect of the air pressure in the unsaturated zone on the performance of the ground pavements is largely ignored in the current practice of pavement design. It is well known that the strength of materials under cyclic conditions is significantly lower than for monotonic loading and that the repeated loading leads to decreasing bond strength and to increasing slip displacement. The performance of concrete or asphalt surface under the cyclic loading derived from the tidal-induced air pressure in the unsaturated soil below the paved ground surface needs to be evaluated.

4 Conclusions

This paper investigates the airflow in the unsaturated zones induced by tidal fluctuation. Observation shows that significant air pressure can be generated by water level fluctuation in a coastal area capped by low-permeability surface of great areal extent. A two-dimensional cross-section model is constructed to describe the air-water two-phase flow below the asphalt way of a coastal reclamation area in Hong Kong. TOUGH2 simulation program is used to obtain the numerical solutions. The numerical simulation demonstrates that the air pressure is approximately proportional to the tidal rate. Coastal unsaturated zones inhale and exhale as the tidal level falls and rises. It is believed that understanding airflow induced by tidal fluctuation may be of not only theoretical interests but also practical significance. The cyclic fluctuation of the air pressure in coastal unsaturated zones may have various environmental and engineering implications and will be a topic of further investigation.

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