Full Scale Test on Cost Effective Liquefaction Countermeasure for a Highway Embankment*

Mitsu OKAMURA

(Graduate School of Science and Engineering, Ehime University, Matsuyama, Japan)

Abstract: Desaturation of ground by air injection attracts considerable attention in recent years as an innovative cost effective technique for liquefaction countermeasure. This paper describes an in-situ air injection test which aimed to verify effectiveness of the use of higher air injection pressures to desaturate very wide zone from a single air injector. In the test, air was injected in liquefiable foundation soils immediately below a highway embankment. Observations revealed that the soil around the injector was desaturated effectively and the zone of influence extended more than 9 m from the injector. This radius was about 5 times larger than that achieved in the past test, leading to a dramatic reduction in execution cost.

Keywords: liquefaction, countermeasure, desaturation, embankment

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Introduction

Liquefaction countermeasure techniques have been used to ameliorate liquefaction resistances of loose sand deposits. Most of the techniques, however, are only available for improving foundation soils without any structures. Techniques that are applicable to soils blow existing structures are limited and particular costly, if any. A challenge that geotechnical engineers have been facing is that the remedial countermeasure works for a large number of existing structures including road embankment, river and coastal levees which are susceptible to liquefaction induced damage.

Desaturation of ground by air injection (Okamura *et al*, 2011) attracts considerable attention in recent years as an innovative technique for liquefaction countermeasure, largely due to its cost effectiveness. The execution cost of the technique is approximately one - tenth of the other techniques available for soil improvement below existing structures. But the cost is still too extensive for such long structures as road embankments and river levees, since the volume of liquefiable soils below the linear long structures are huge. This is because ground improvement for liquefaction countermeasure has never executed for highway embankments.

Okamura *et al* (2011) has conducted in-situ tests where air was injected at a depth of 6 m with the injection pressure of 45 kPa (the hydrostatic pressure 32 kPa + the net injection pressure 13 kPa) in Kochi prefecture, Shikoku. The influence zone where soil was effectively desaturated extended around the injection point with a diameter of about 3.5 m. The execution cost of the technique at this time was similar to those ground improvement techniques such as sand compaction piles. This is still far beyond allowable cost to remediate long road embankments which is susceptible to liquefaction damage.

Since the material of this technique is air alone, installation cost of injection pipes occupied a larger part of execution cost, more than a half. Reduction of the number of injection pipes will make this technique more cost effective. For soils directly below high embankments, because of higher effective overburden pressures, air injection with higher injection pressure can be executed without disturbing soils. It has reported that the higher the injection pressures, the wider the zone of influence around an injection pipe (Yasuhara

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et al, 2008).

This paper describes an in-situ air injection test at a highway embankment aiming at verifying the effectiveness of the use of higher air injection pressure to widen the zone of influence and reduce the number of injection pipe by applying a higher injection pressure.

1. Factors Controlling Liquefaction Resistance of Unsaturated Sand

Existence of air in pores of soil is considered to enhance a liquefaction resistance. Air in the pores plays a role of absorbing generated excess pore pressures by reducing its volume. Change in volume of the pore fluid, that is air water mixture, may be the factors dominating this mechanism.

Considering a soil mass of its pore filled with air and water. For a small change in the pore pressure Δp, we obtain the volumetric strain of the soil using the Boyle's law as

$$\varepsilon_v = \frac{\Delta p}{p_0 + \Delta p}(1 - S_r)\frac{e}{1+e} \leq \frac{\sigma_c{}'}{p_0 + \sigma_c{}'}(1 + S_r)\frac{e}{1+e} \equiv \varepsilon_v{}^*. \quad (1)$$

Where p_0 and e denote the pressure of the fluid and the void ratio of the soil mass respectively. In the above equation, compressibility of soil grain and water is ignored. The highest value of the volumetric strain for a soil is achieved when the Δp attains its possible maximum value which is equal to the effective confining stress $\sigma_c{}'$. This highest value of the volumetric strain is hereafter termed as the potential volumetric strain, $\varepsilon_v{}^*$.

Effects of the factors appeared in Eq.(1) were individually investigated through a series of triaxial tests on Toyoura sand specimens at a relative density of 40%. Three testing parameters including the initial effective confining pressure, $\sigma_c{}'$, the buck pressure and the degree of saturation S_r, were varied between tests while the void ratio of the specimens was kept as a constant throughout the test series. It should be noted that the back pressure p_0, is the absolute pressure instead of the ordinary used gauge pressure. It was found that the liquefaction resistances of the partially saturated sand increase with the initial confining pressures, with the liquefaction resistances being higher for lower S_r. Also the liquefaction resistance depends on the back pressure; the liquefaction resistance decreases as the pressure increases (Okamura, Soga, 2006).

The liquefaction resistance ratio, which is the liquefaction resistance of partially saturated sand normalized with respect to that of fully saturated sand, is plotted against the potential volumetric strain in Figure 2. All the data lies along a unique curve, confirming that the potential volumetric strain is the determining factor of the effect of degree of saturation on this specific sand at relative density of 40%. It was also found that data retrieved from literature, which was obtained from tests on specimens prepared using different sand at different relative densities and at different confining pressures, lies along the same curve (Okamura, Soga, 2006). This indicates that the effect of the degree of saturation on liquefaction resistance is dominated by the factor $\varepsilon_v{}^*$.

2. Air Injection below Highway Embankment

2.1. Test Site of In-situ Air Injection

The test was conducted at a construction site of highway embankment of the West Nippon Expressway Company near the mouth of Imagiri River, Tokushima prefecture, as shown in Figure 1.

Figure 3 indicates the soil profile at the site. Alluvium loose sand deposit extends from the surface to the depth of about 12 m. This layer was judged liquefiable and set as the target layer of desaturation by air injection. Fines content of the layer was mostly lower than 20% and several thin clay seams being sandwiched. The ground water table was below 0.5 m from the surface. Soil water retention characteristics were tested on disturbed samples with a pressure plate apparatus and the minimum pressure observed at the onset of drainage, recognized as an air entry value, was in a range between 1 kPa to 10 kPa.

Figure 4 shows a more detailed boring log and locations of air injectors. There were several thick clay seams at the depths of 5 m and between 9 m and 12 m. As these clay seams were expected to impede upward flow of injected air, injectors were set at several depths so that the whole the sand layer can be desaturated. In order to monitor the evolution of desaturated zone during injection, electrodes were installed at intervals of 2.5 m in plan and 0.5 m in depth. Electric resistivity of soil depends on several parameters including water content, void ratio, temperature, ionic content, resistivity of solid phase, particle size and pressure. The influences of these factors on the resistivity may be dissimilar among different soil types, however, desaturation technique by air injection does not alter these parameters with only exception of volumetric water content (degree of saturation). Therefore, change in the electric resistivity during air injection is expected to be uniquely related to change in the degree of soil saturation.

2.2. Air Injection

Air injection was conducted one by one from each air injector. In this paper, two injection processes at a depth 8.3 m in the A-1 hole and 8.2 m in the S-1 hole are discussed. The photo of the injection controlling system at the site was depicted in Figure 5. In the injection test, injection air pressure increased gradually until injected air started flowing into soil. The pressure was found to be 80 kPa.

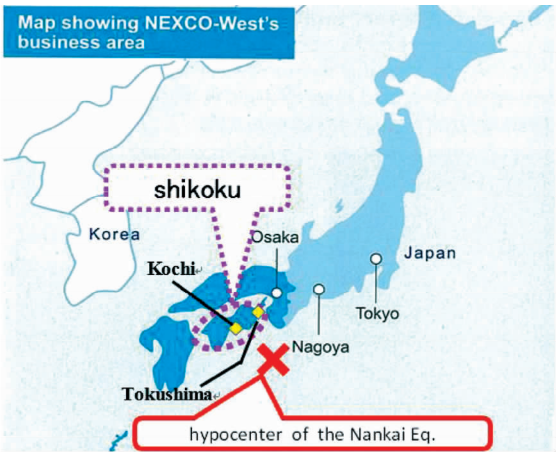


Figure 1. Locations of the expected Nankai Earthquake and Shikoku where in-situ tests were conducted

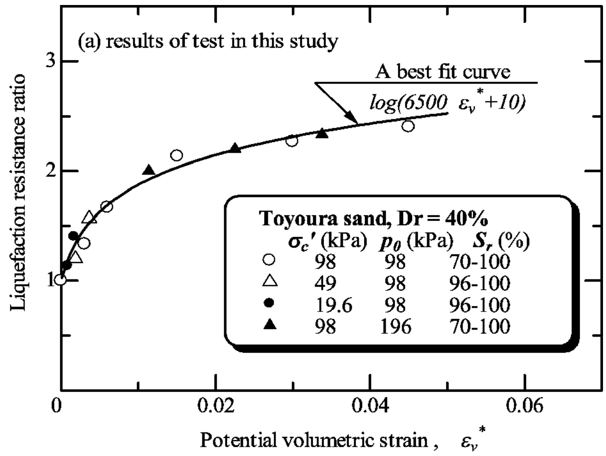


Figure 2. Relationship between potential volumetric strain and liquefaction resistance ratio

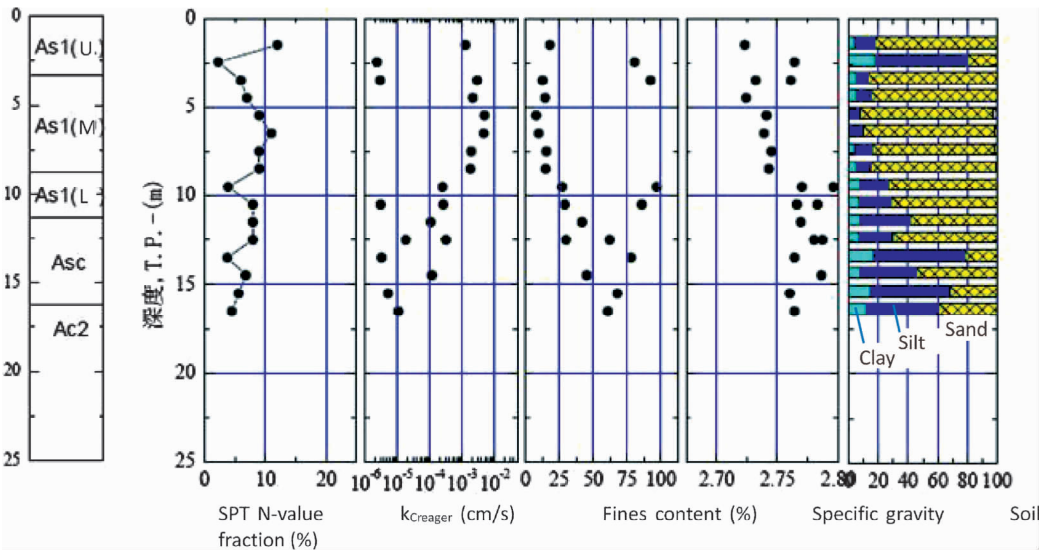


Figure 3. Soil profile at the test site

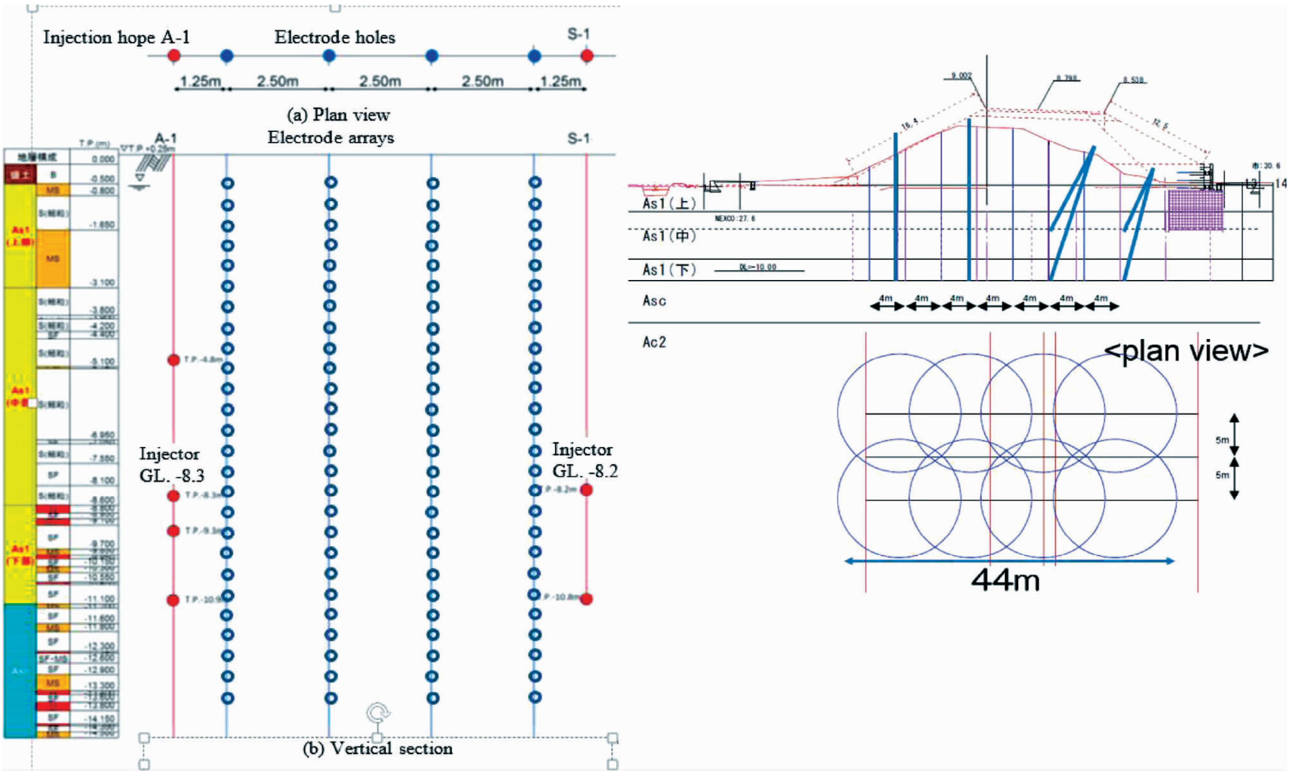


Figure 4. Arrangement of air injectors and electrodes

Figure 5. Air injection system at the site

At the injection point, the effective vertical stress and the hydrostatic pressure were approximately $\sigma_v' = 100$ kPa and $P_{hyd} = 75$ kPa, respectively. The injection pressure increased further to 150 kPa, which is sum of P_{hyd} and two thirds of σ_v'. Figure 6 depicts time histories of injection pressures and flow rate. Air flow rate increased with time while the pressure was kept to be constant, suggesting that the desaturated zone expanded and degree of saturation of soil in the zone decreased.

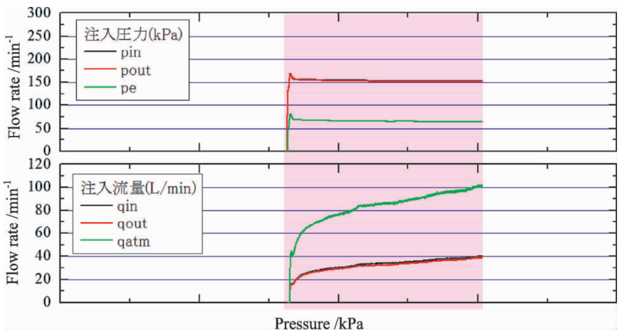
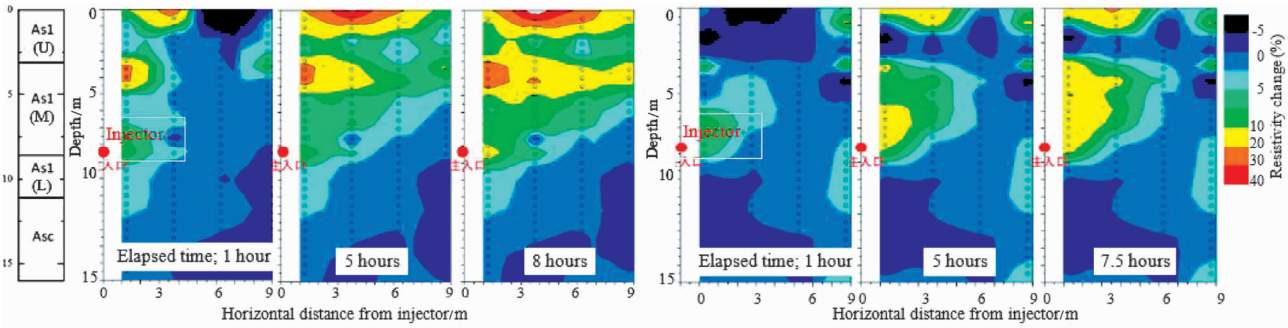


Figure　6. Time histories of pressures and flow rate of injected air

2.3. Results and Discussions

Figure 7 indicates variations in the electric resistivity change $(\rho_a - \rho_b)/\rho_b$ observed during injection at 8.3 m in A - 1 hole, where ρ_a and ρ_b denote the pre- and post-injection resistivity, respectively. The yellow and red zones in the figure corresponds to resistivity increase due to the decrease in degree of saturation by the air injection. The desaturated zone seems to have extended diagonally upwards from the injection point with time. At 7.5 hours after initiation of injection, the zone of influence at the depth of injection point extended about 5 m and more than 9 m at a shallower depth. More than 16 hours after halting the injection at the A - 1 hole, which was considered to be long enough to dissipate excess pore pressures, very similar injection test was conducted from the S - 1 hole. Although the zone of influence was somewhat narrower than the injection from the A - 1 hole, soils in the radius of 5 m was effectively desaturated in 6.5 hours.



(a) Air injection from A - 1 hole (b) Air injection from S - 1 hole

Figure 7. Evolution of the electric resistivity change

The diameters of the zone of influence attained in the tests are more than three times larger than that observed in the previous test at the Kochi site (Okamura *et al*, 2011). This means that the number of boring wholes for air injector can be reduced less than one ninth, resulting in very significant reduction in execution cost. The most important difference in test conditions between this study and Kochi site is the net injection pressure, i.e. air pressure at an injector minus hydrostatic pressure. Since injected air tends to flow upward owing to the buoyancy force, a higher injection pressure pushes the injected air not only upward but also horizontally. Higher pressure is also effective to desaturate soil more uniformly. Since the natural soil is inherently heterogeneous and injected air tends to flow only within preferential path ways where permeability is high and soils outside the ways will be remained in saturated condition. Application of higher air pressure, that is higher suction pressure, can be effective to reduce such a heterogeneous distribution in degree of saturation in the zone of influence.

3. Gas - liquid Two - phase Flow Simulation of In - situ Test

3.1. TOUGH2 Simulation

Air injection at a certain location underground creates influence zone around the injection point. During the air injection, simultaneous flow of water and air occurs, and thus the effects of capillary pressures and the mutual flow interaction between the two phases should be addressed in a computational manner. In this study, a gas - liquid two - phase simulator TOUGH2 (Pruess *et al*, 1999) that accounts for the above requisites was utilized to estimate the extent of the influence zone.

In TOUGH2, a mass balance may be expressed in integral form for arbitrary sub-volume V_n, bounded by a surface area of Γ_n, given as

$$\frac{d}{dt}\int_{V_n} \boldsymbol{M}^K dV_n = \int_{\Gamma_n} \boldsymbol{F}^K \cdot \boldsymbol{n} d\Gamma_n + \int_{V_n} \boldsymbol{q}^K dV_n. \quad (2)$$

where K denotes the component, M^K is the amount of component K with a dimension of mass per volume, F^K is the flux of component K, n is the outward unit vector normal to the volume surface, q^K is the rate of generation of component K within the volume.

Eq. (2) is discretized in space to numerically solve multiphase flow processes. After discretized as a first – order finite difference, the flux and sink and source terms are evaluated at the next time step. An iterative procedure is adopted to solve in time until a prescribed time.

The simulated domain with a dimension of 28 m wide and 13 m deep has no – flow boundaries for both water and air except a top surface boundary open for flow, and has be five different layers as shown in Figure 8, compatible to Figure 3. Air pressure exerted at injection points is fixed to 150 kPa following the in – situ test condition. The hydraulic conductivity for each layer was evaluated by constant – head permeability tests using the boring samples. The relation between the capillary pressure and the degree of saturation for each layer was determined through soil water retention experiments, together with the well – fitted predictions.

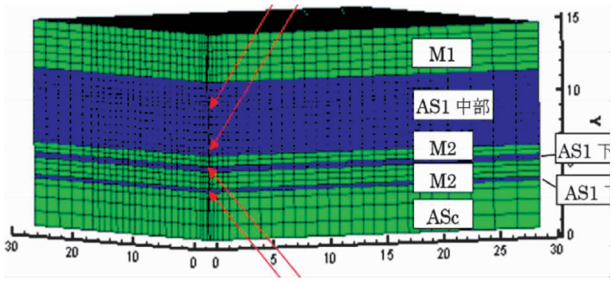


Figure 8. Mesh for TOUGH2 simulation

3.2. Comparison between Observations and Predictions

Predictions of the evolution in degree of saturation utilizing the ground model and parameters constrained in the previous section are shown in Figure 9. A desaturated bulb augments as the prediction proceeds both upward and laterally, and upward evolution is impeded by the bottom of clay layer at – 3.1 m. This is quite similar to that observed in the injection from S – 1 hole. Although in-situ observations did not provide magnitude of degree of saturation, observed electric resistivity (Figure 7) and simulated degree of saturation (Figure 9) are qualitatively quite comparable. This indicates that the model may be capable of predicting desaturation processes mediated by air injection

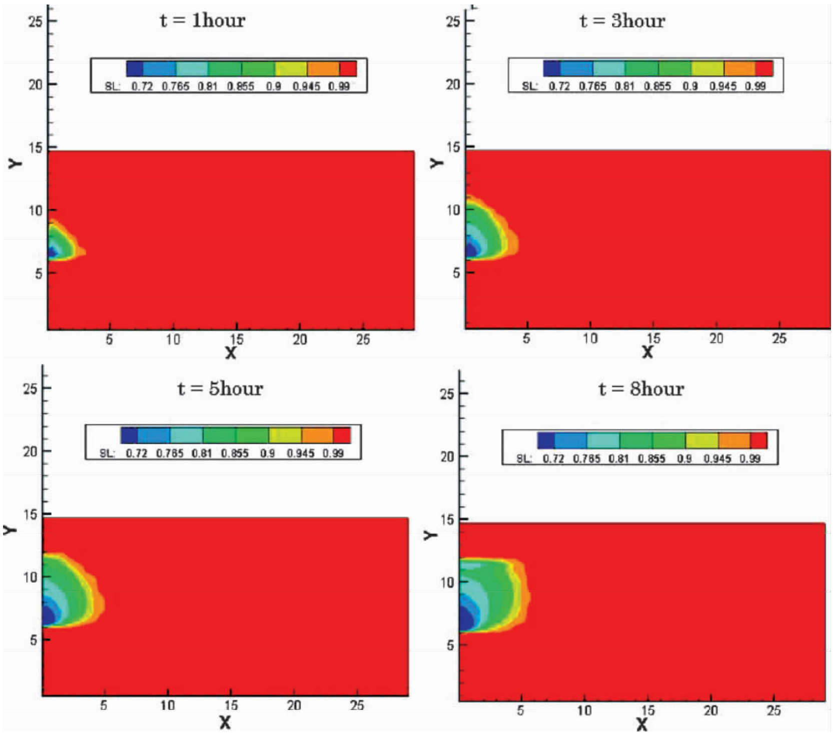


Figure 9. Predicted evolution in degree of saturation during air injection

under arbitrary conditions, and be applicable to field problems as flow characteristics are identified.

4. Conclusions

In this study, an in-situ air injection test was conducted which aimed to examine the effectiveness of the use of higher air injection pressures to desaturate very wide zone from a single air injector. In the test, air was injected in liquefiable foundation soils immediately below a highway embankment with the net injection pressure as high as 75 kPa. Observations revealed that soils around the injector effectively desaturated and the zone of influence extended more than 5 m from the injector. This radius is about 3 times larger than that achieved in the past test, leading to a dramatic reduction in execution cost.

The in-situ injection tests were numerically simulated with a gas – liquid two phase flow simulator TOUGH2. The simulated desaturated zone augments as time in very similar manner to the evolution of observed electric resistivity change. The simulator may be capable of predicting desaturation processes mediated by air injection under arbitrary conditions, and be applicable to field problems as flow characteristics are identified.

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有效的防止高速公路路堤沙土液化对策执行成本的全尺度检验

Mitsu OKAMURA

(Graduate School of Science and Engineering, Ehime University, Matsuyama, Japan)

摘要：近年来，通过空气注射法稀释地基饱和度作为一种创新性并且具有成本效益的防止液化的技术得到了广泛关注。本文描述了一种现场空气喷射试验，旨在验证使用单一空气喷射器喷射更高喷射压力减少大面积区域饱和度的有效性。在试验中，空气被注射进公路路堤下方的可液化地基土体。观测结果显示：有效地降低了喷射器周围土壤的饱和度，并且喷射器的影响区域超过 9 米，该影响半径约为以往测试值的 5 倍，将直接大幅减少执行成本。

关键词：液化；对策；饱和度；路堤