# Transport of fluids and aggressive agents from the environment into concrete materials

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## Introduction

Concrete materials are used in the construction of a wide range of infrastructures. Many of them are exposed to a variety of serious environments during their service life. Their durability strongly depends on the transport of fluids and/or aggressive agents from the environment into the concrete materials.

The transport of fluids and ionic species from the environment into concrete materials can take place through pore spaces in the cement paste matrix, interfacial transition zone and cracks, according to the following 4 mechanisms, ① permeation due to a pressure gradient,; ② diffusion due to a concentration gradient; ③ absorption due to capillary action; ④ migration due to an electrical potential gradient.

Corrosion of steel reinforcement due to the ingress of air-born salt into concrete has been the main reason for the deterioration of concrete bridges in marine atmosphere zone. Air-born salt refers to sea salt aerosol particles which are formed predominantly by the action of wind on the ocean. Penetration of chloride into concrete is a complex phenomenon involving various factors, including diffusion of chloride ions in pore liquid and their movement with water within concrete. The latter process conveys a greater quantity of chloride ions than the diffusion process does, especially at the outmost surface zone of concrete structure in real unsaturated situation site.

In order to investigate the air-born salt environment and adherent chlorides on the surface of bridge along seashore, we have carried out a series of experimental observation at Amadori Bridge in the south of Wakayama Prefecture facing Pacific Ocean in the past 4 years. Details are present in the following.

## Effect of Environmental Factors on Chloride Ingress

Amadori Bridge is a steel bridge with 3 I-type girders (**Figure 1**). One side of the bridge faces the sea, the opposite side faces a cliff. Mortar panels with size of 4×4×0.5 cm (**Figure 2**) were adhered to 30 locations on the surface of the girders to investigate the spatial distribution of air-born salt penetration along the transverse. Meanwhile, the amount of salt deposition on the steel surface beside mortar specimen was also measured. The observed results are shown in **Figure 3**, along with evaluated results based on CFD calculation. It is found that for the same bridge site, the salt deposit on steel surface or on the surface layer of concrete could be largely different, which would bring different degradation rate and level in one bridge structure. This phenomenon comes from micro –environment condition at each local position, such as rainfall, humidity, temperature and sunshine etc. Meanwhile, mortar specimens were also exposed under the bridge and near the sea separately (**Figure 4**) for 4 periods to investigate the effect of rainfall. Dashed lines in **Figure 5** refer to those near the sea, presenting lower concentration of chloride ion than solid lines which refer to those under the bridge. This gives an obvi-

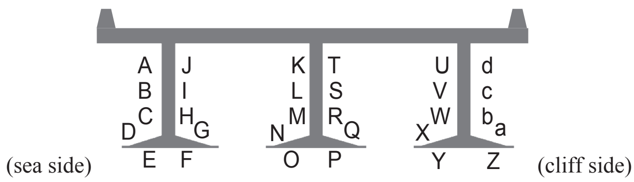

Figure 1. Location of mortar panels

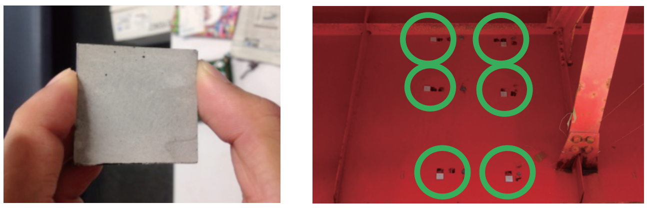
Figure 2. Mortar panels

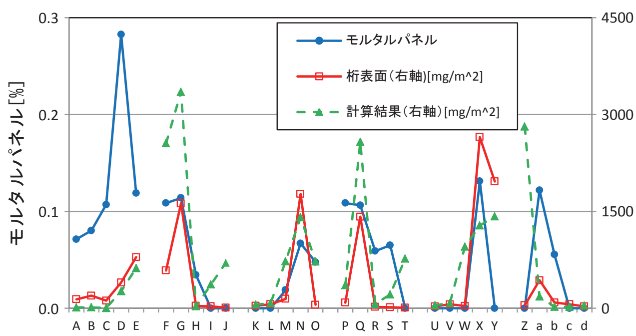

Figure 3. Location of mortar panels (2015.7.23~9.30)

Figure 4. Exposure of mortar specimens

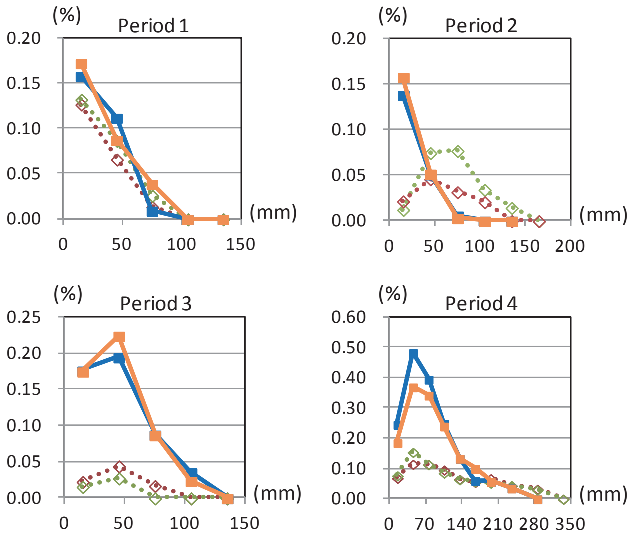


Figure 5. Concentration distribution of Chloride ion in mortar specimens during 4 periods (2015-2017) observation

ous conclusion that rainfall may clean the salt to some degree and also may change the concentration distribution of chloride ions at the surface layer of concrete material.

**Monitor of Substance Migration by POF**

A new method of monitoring complex behaviors of geo-materials using plastic optic fiber (POF) was proposed by Akutagawa et al. Unlike in conventional methods of using optic fibers for engineering monitoring, the new method uses tip of POF as monitoring points. As the path and properties of light is affected by many factors shown in **Figure 6**, originating from mechanical, hydrological, electrical, chemical and biological phenomena happening near the fiber tip, a qualitative interpretation of the obtained signal to identify exact situation of the monitoring zone becomes possible. A twin fiber sensor with 45 degree inclination is shown in **Figure 7**. The light intensity ratio of refracted light L5 over incident

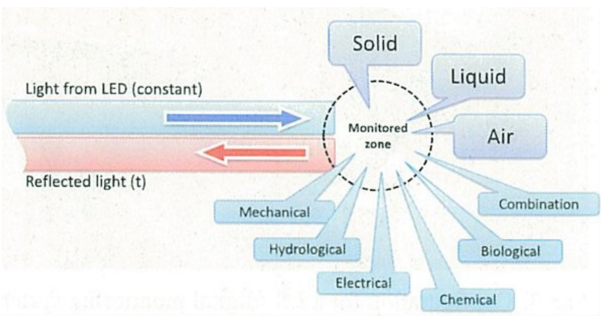


Figure 6. Factors affecting properties of returning light

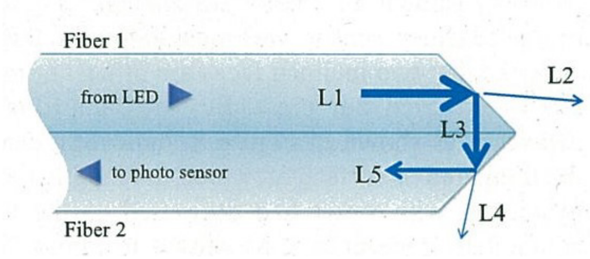


Figure 7. Paths of light around inclined faces of two POFs

light L1 can be determined from refractive indices of materials. We are trying to do a series of experiments to monitor the hydration process of various concrete materials, correlating the relationship between hydration properties with the change of light intensity. Also, POF is embedded in hardened concrete to monitor the passage of water or passage of other ionic solution, drying and wetting process and so on.

**The Future work**

Geopolymer concrete (GPC) is considered as the 3rd generation cement after lime and ordinary Portland cement. For GPC, Portland cement is not used as a binding material. Instead, industrial by-product materials rich in Silicon and Aluminum such as fly ash, rice-husk ash, silica fume, slag, and other similar materials are added to react with highly alkaline liquid to produce binders. The polymerization reaction under highly alkaline condition is substantially fast on silicon-aluminum minerals resulting in a three-dimensional polymeric chain and ring structure. The use of this geopolymerization process in concrete-making could significantly reduce the $CO_2$ emission into the atmosphere caused by cement industry. It further reduces or eliminates the need for large amounts of raw materials for the manufacture of Portland cement and provides additional potential for recycling of Al and Si rich by-products materials.

In the past two decades, although significant progress has been made, there is an immense need for an understanding of setting reactions, the relationship between mix design characteristics, the short and long term mechanical properties and overall durability. Our research in GPC will focus on its various durability properties, especially the transport of fluids and aggressive agents from environment. Bond behavior between reinforcement and GPC, corrosion of reinforcement in GPC are also of our interest.

## 表面流と浸透流の同時解析手法の構築と堤防侵食への適用

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### はじめに

近年，局地的集中豪雨に起因する河川堤防の破堤が発生しており，人口と資産が集中する堤内地に甚大な被害をもたらしている．したがって，堤防の安全性を評価する要素技術の開発は，減災対策を進めていく上で極めて重要な課題であると考えられる．

堤防の安全性を評価するには，出水時における表面越流の非定常流れ（水位や流速の時間的・空間的変化），堤体内の浸透過程を精度よく予測するとともに，越流による表面侵食や水の浸透に伴って土の有効応力が減少し，破壊に至るメカニズムを再現して対策を考えることが必要である．

しかし，これまで適用されてきた予測モデルでは，平面2次元モデルによって表面流場が計算されており，堤体近傍の流れの再現性が低いと思われる．また，流れ場が空間的に変化し，それに伴って複雑な土砂輸送特性を示すにも関わらず，その土砂輸送プロセスも十分に考慮されていない．したがって，河川堤防の破堤に対する安全性評価法について，精度の高い予測技術は確立できていないと考えられる．

そこで本稿では，堤防の越流侵食過程を精度よく予測できる数値解析モデルを紹介するとともに，その適用例を示す．

### 数値解析モデルの概要

堤防周りの表面流と堤体内の浸透流を同時に予測できる3次元流体解析モデルと，越流によって引き起こされる土砂輸送モデルをカップリングした．3次元流体解析モデルには，非定常流れの水面変動を考慮するため，密度関数法を用いるとともに，3次元数値解析の計算格子において水域，堤体内とその境界面を容易に表現し，堤体への浸透を考慮するためにポーラスメディア法を適用した．基礎式は以下のとおりである．

$$\frac{\partial(1-c)\Phi}{\partial t}+\frac{\partial(1-c)u_j\Phi}{\partial x_j}=0 \qquad (1)$$

$$\begin{aligned}&\frac{\partial}{\partial t}\{(1-c)u_i\}+\frac{\partial}{\partial x_j}\{(1-c)u_iu_j\}\\&=(1-c)g_i-\frac{(1-c)}{\rho}\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left\{-(1-c)\overline{u_i'u_j'}\right\}\\&+\nu\frac{\partial}{\partial x_j}\left\{(1-c)\frac{\partial u_i}{\partial x_j}\right\}-\frac{\nu(1-c)^2u_i}{K_d}\end{aligned} \qquad (2)$$

ここで，$x_i$：デカルト座標系，$t$：時間，$u_i$：流速ベクトルの$x_i$方向成分，$\Phi$：密度関数，$c$：固相の体積濃度，$u'_i$：乱れ速度ベクトル，$p$：圧力，$\rho$：流体の密度，$\nu$：動粘性係数，$g_i$：重力加速度ベクトル，$K_d$：固有透水係数である．添え字$i, j$は1, 2, 3の値をとり，1, 2, 3はそれぞれ$x, y, z$方向を表す．式(2)の右辺最終項は抵抗力であり，ここでは簡単のためDarcy則を適用した．また，計算格子における水域，堤体内とその境界面の区別は固相の体積濃度cで表現し，堤体内とその境界面の体積濃度については，$c = c_0V_s/V_c$（$c_0$：堤体材料の体積濃度，$V_s$：計算セルにおいて堤体材料が占める体積，$V_c$：セル体積）より求めた．

次に，表面越流侵食での土砂輸送モデルについて説明する．越流侵食過程では堤頂部から裏法部にかけて急激に流砂量が変化するため，流砂の非平衡性を考慮する必要があると考えられる．そこで，水制周辺の局所洗掘を再現した非平衡流砂モデルを適用した．非平衡流砂モデルは，pick-up rateの算定，砂粒の運動方程式より砂粒群の移動経路の計算，step lengthに応じたdeposition rateの算定によって構成されている．

### モデルの適用

上記の数値解析モデルを正面越流による堤防侵食過程[1)]に適用し，モデルの妥当性を検証した．計算領域を**図1**に示す．矩形断面開水路中に高さ0.2 m，天端幅0.1 m，法面勾配1：2の堤体が乾燥砂の状態で設置されており，河床材料の粒径は2 mmである．計算格子数は，流れ，横断，鉛直方向にそれぞれ225, 10, 35とし，$\Delta x, \Delta y, \Delta z$は0.02 m, 0.02 m, 0.01 mである．初期条件として，計算領域には水を入れず，上流から定常流量を与え，流れの計算を行う．表面流が堤防天端を通過した時刻を$t$ = 0sとし，土砂輸送計算を開始した．

**図2**は流況の時間変化を示したものである．上流から流れてきた水が堤防を越流するとともに，堤体へ浸透していく様子が確認できる．

**図3**は堤体形状の時間変化について実験結果と計算結果を比較したものである．横軸$X$は$(x - x_D)/L_D$，縦軸$Z$は$z/h_D$であり，**図1**に示した諸量により無次元化している．$t$ = 2.8 s, $t$ = 5.7 sの図をみると，堤防の侵食は裏法肩から始まり，侵食に伴って天端幅が短くなる特徴が捉えられている．侵食された土砂は裏法尻に堆積しているが，実験結果に比べると計算結果の堆積は若干少ない．さらに，その後の結果を比較すると，表面流による侵食によって，堤防の高さが低くなっていくとともに，堤体形状がなだらかになっている様子が確認できる．以上の結果から，本数値解析モデルは堤防の越流侵食過程を概ね再現できると考えられる．なお，本研究の詳細については参考文献[2)]をご覧いただきたい．本稿では，流れ解析モデルと表面流による土砂輸送モデルをカップリングすることで越流侵食過程の数値解析を行ったが，この流れのモデルでは表面流と浸透流を同時に予測しているため，間隙水圧を求めることができる．今後，地盤工学に基づいた土の変形モデルと連成させることで，堤防の浸透破壊にも適用したいと考えている．

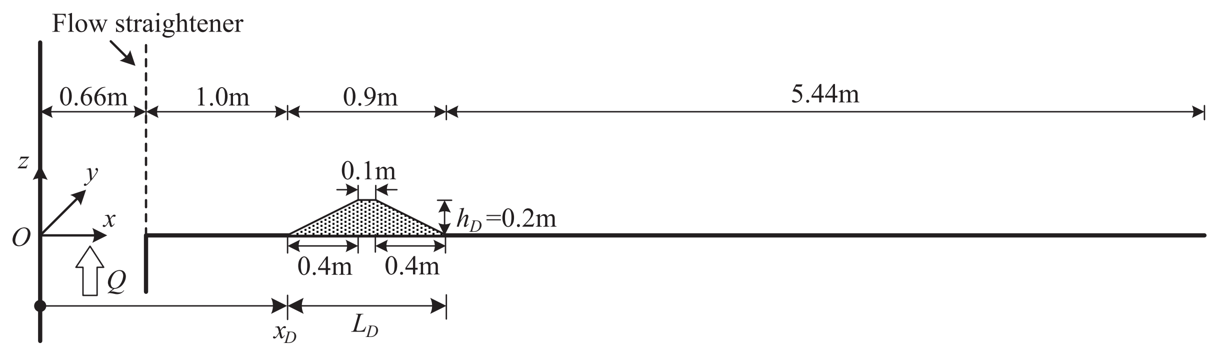


図１　計算領域

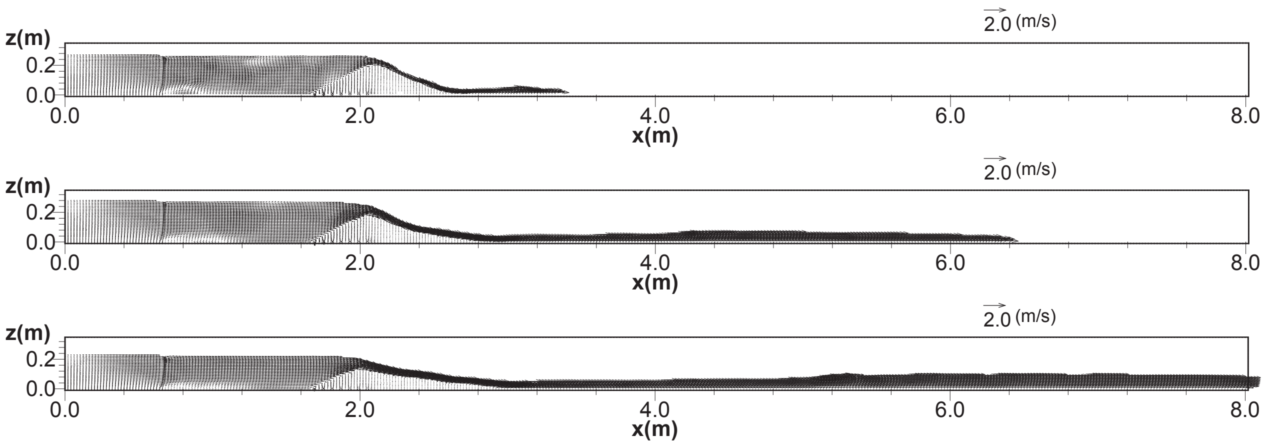


図２　流況の時間変化（上：$t = 2.8$ s，中：$t = 5.7$ s，下：$t = 14.1$ s）

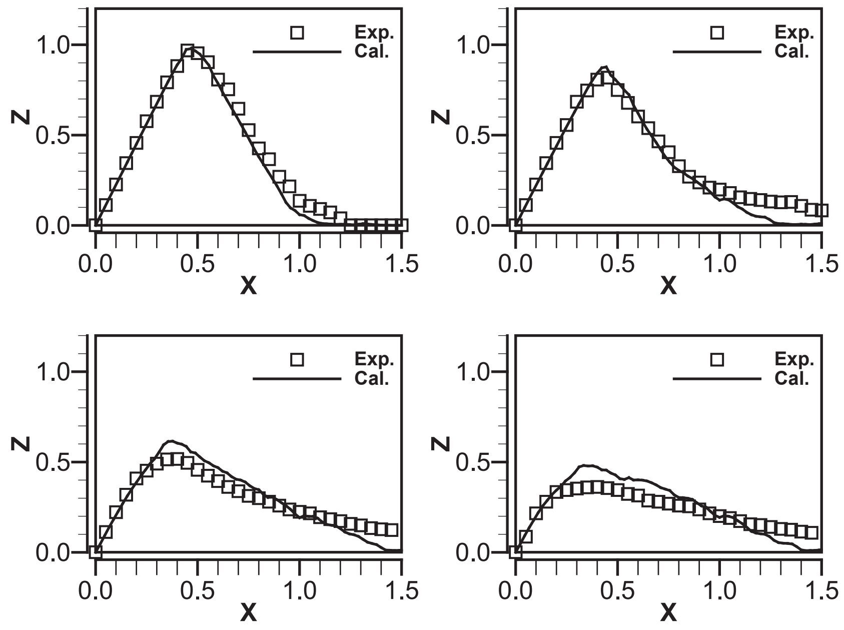


図３　堤体形状の時間変化（左上：$t = 2.8$ s，右上：$t = 5.7$ s，左下：$t = 14.1$ s，右下：$t = 28.3$ s）

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# Development of centrifuge modeling of embankment constructed on soft ground subjected to seismic loading

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## Introduction

After the 2011 Off the Pacific Coast of Tohoku earthquake, many researches have been conducted with an aim to answer why a large number of embankments and levees resting on non-liquefiable foundation soils were severely damaged. Despite Tohoku Regional Development Bureau of Ministry of Land, Infrastructure, Transport & Tourism (MLIT) had summarized that damages caused by liquefaction of the foundation ground involve basal settlement and saturated condition of loosening construction materials inside levees submerged under water, the failure mechanism has not been clearly understood because these explanations are not much different than what have been pointed out since the occurrence of the 1993 Off Kushiro-Oki earthquake. Previous experimental works successfully confirming the main causes of liquefaction mentioned earlier reported that stress at the lower part of the embankments was reduced after the embankments underwent subsidence due to the consolidation of the foundation clay. This result implies “soil arching”; however, “arching effect” was not mentioned. In fact, previous theoretical works have already found that the settlement of embankments induces arch action across a basal deflection in an attempt to explain the phenomenon of central pressure drop observed in granular heaps with a deflected base. It might not be realized on that time this counter-intuitive observation could be related to the occurrence of liquefaction.

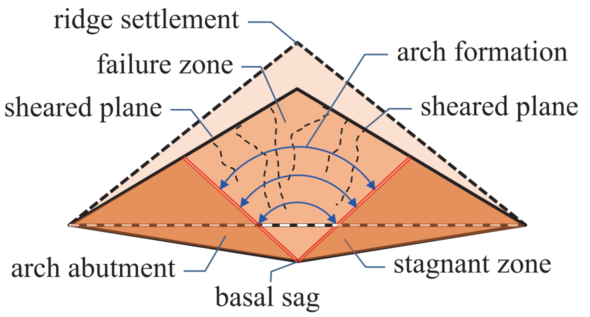


Figure 1. Mechanisms causing sheared plane and failure zone observed in 1G physical model of embankment with basal sag. As arching is ability to transfer load laterally, formation of arch needs relative displacements between the stagnant and mobilized zones.

As explained in **Figure 1**, arching effect in embankments is separated into active and passive arch actions. 1G embankment models with hysteretic loops of basal settlement have been developed, confirming the downward basal deflection significantly induces passive arch and numerical lower-bound limit analyses can characterize the pressure profiles with the hump profile in active condition and the pronounced dip in passive condition.

## Research objectives

This research aims at associating the arching phenomena in soils with the mechanisms of weakening resistance against liquefaction of partially saturated embankments resting on deformable ground. Secondly, to develop the experimentally realizable theory bridging the criteria of arch collapse and the failure of embankment due to liquefaction and strong ground motions. A series of both 1G model tests in static loading and centrifugal model tests of embankment in dynamic loadings is carried out to diagnose the mechanisms of arch collapse.

Herein, the scope of research is limited to liquefiable embankments resting on the soft ground with the primary objective focusing on whether embankments constructed on deformable foundation is unsafe because passive arch action weakens the liquefaction resistance and insufficient confining pressure fails to prevent overstress in soil arching against seismic forces, or by other combined factors. Therefore, the following unclear mechanisms will be elucidated step by step during the research period using physical modelling and numerical analysis.

1) Before earthquake: basal settlement → arch action → weakening liquefaction resistance (see **Figure 2**)
2) After earthquake: soil liquefaction → drop of confining pressure + seismic force → arch collapse → failure of embankment (see **Figure 3**)

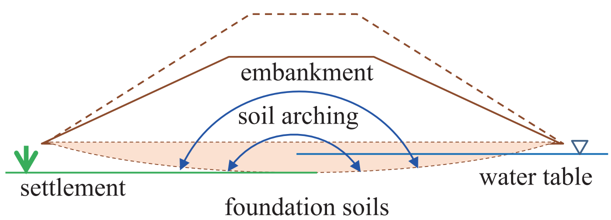


Figure 2. Arches are formed due to basal settlement, causing central pressure drop; hence reducing the resistance against liquefaction.

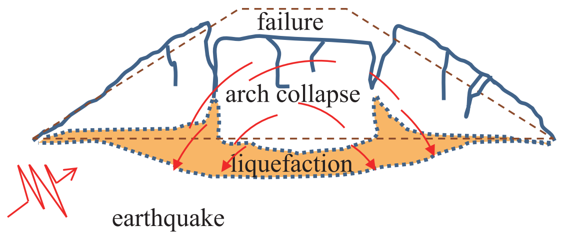


Figure 3. Earthquake induces liquefaction in saturated loose materials within and underneath embankment; consequently, liquefied soil further reduces the confining pressure to the arch abutments; therefore, the abrupt buckling of force chains causes a severe damage to the embankment.

### Evaluation process

The model configuration and instrumentation is shown in **Figures 4 and 5** in which the deformable ground was modelled by Urethane. The basal subsidence was recorded by a couple of laser sensor transducers. One pointed directly on the crest surface to measure the total subsidence while the other pointed on the wooden rod connected with the base to measure basal subsidence separately. Two pore water pressure transducers were used together with three earth pressure gauges to measure both vertical and horizontal earth pressures for observing the occurrence of arching effect. The fluid was prepared by dissolving Metolose with water to achieve 50 cSt kinematic viscosity fluid for centrifuge tests at acceleration of 50g.

### Summary and conclusion

Dynamic centrifuge model tests of embankments placing on rigid base and soft base modelled by Urethane were conducted to investigate the liquefaction resistance in association with the change of the stress distribution inside embankments due to basal subsidence. As demonstrated by **Figure 6**, experimental results reveal that lateral spreading deformation causes reduction in horizontal earth pressure along the bottom of highly-compacted embankments due to concave settlement of the base.

Moreover, arch action formed underneath the core of embankment with reduction in vertical earth pressure was observed due to the basal subsidence and loosening of inner zone after submersion by Metalose supplied inside the embankment. Comparisons between embankments built on the Urethane ground and those built on rigid ground imply that basal subsidence decreases liquefaction resistance in embankments during an earthquake.

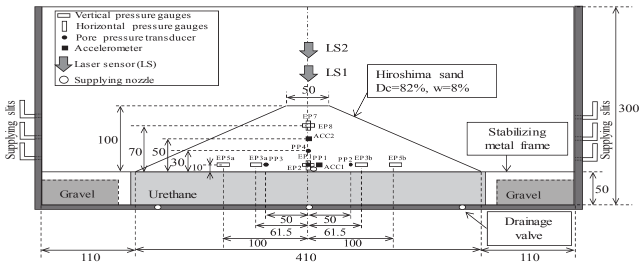


Figure 4. Model configuration and instrumentations

Figure 5. Soil chamber loaded in centrifuge facility at DPRI

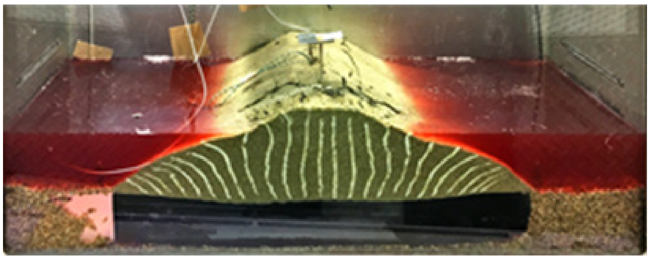

Figure 6. Failure of embankment model after shaking

### Expected outcome

The outcome of this research will provide a key idea to mitigate embankments from earthquake disasters by providing a new design concept and the rational determination of the required reinforcement along the minor principal axes of soil arching or confining pressure to the existing embankments.

## Public Transport Fare Structure Issues: Trends and Modelling Challenges

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### The Public Transport Fares Debate

How to set appropriate public transport fares has always been a hotly debated topic. Fares have a crucial influence on the attractiveness of public transport systems. They are often seen not only as an economic but a wider political issue that affects residents' accessibility, social inclusion, equity and with it their quality-of-life. Fares are further related to spatial equality and economic conditions including local policy issues such as land-value capture, income taxation and urban sprawl.

Recently a number of operators are changing the structure of their fare system significantly. In some cities simple flat fare structures or zonal based fare structures are replaced by distance-based charges. In particular the introduction of mobile-phone based ticketing where the fare is determined through GPS tracking encourages this trend. Whether this leads to "fair fares" is though ambiguous and other cities therefore oppose this step and move in the opposite direction. On the one hand, distance-based fares mean that travelers pay according to what they consume. On the other hand, travelers living far from the city are disadvantaged and often it is exactly this population group that cannot afford higher fares. Therefore in cities such as Santiago de Chile consciously a simple flat fare is operated even for the metro system so that poverty is not amplified through fare policy.

### Trends in European cities

In 2016 a colleague and I conducted a study commissioned by the European Metropolitan Transport Authorities (EMTA) to investigate future fare policy trends among European metropolitan regions. This qualitative research led to **Fig. 1** which illustrates the conflict further. There is a group of cities/regions aiming to simplify their fare structures and another group of cities aiming to diversify their fare structure not only to increase revenue but also to allow for differentiated fares for specific population groups. Therefore a wide range of cities mentioned that their goal is "fair fares" but they aim to achieve this with opposing strategies. Comparing European and Japanese developments, it is noteworthy that in Japan technical integration is far advanced, i.e. SUICA can be used throughout the country, but that fare structure integration is far behind, i.e. most European cities aim for regional fare structures independent of which operator one uses, which is not the case in Japan.


Figure 1. Fare trends in a number of cities/regions. Full report available at http://www.emta.com/spip.php?article693

### Price capping and MaaS

Not to be omitted in the current fare structure debate are further the terms "price capping" and "mobility as a service" (MaaS). The idea of "capping" is that users do not have to calculate in advance anymore whether it is worth purchasing a multiple-ride pass or better to buy tickets for single journeys, but instead travellers use their smart card and the card stops charging them once the daily limit has been reached. London has for example introduced daily and weekly capping. This is certainly convenient for users, whether price capping also leads to significantly increased public transport usage is though to be seen.

MaaS has several connotations, within the fare structure debate the aspects of integrated (possibly mode independent fares) as well as a general "reversed capping" idea that pre-pay for a monthly mobility package is relevant. For example for a fixed price paid in advance, the traveler has the right to use unlimited public transport, taxi within a certain radius as well as a certain number of car sharing trips. How such packages should be priced as well as how they might change behaviour is a key current research issue. Companies offering such mobility packages have started to appear in for example Helsinki, Finland. Especially in Japan the stakes for MaaS appear to be high. The aforementioned fare policy disintegration means that introducing MaaS concepts are difficult. However, the potential winning margins might also be especially high as travelers might value the knowledge that their total payment is fixed more if calculating one`s potential expenditure is difficult. Tourist markets appear therefore a very suitable first market for MaaS type concepts in Japan.

**Modelling Distance-based fares**

Important for the willingness to test and hence success of any fare structure change is the ability to model their potential effects. This is a main challenge for MaaS and capping concepts where one needs to predict wider behavioural impacts but also for simpler fare structures such as the above described changes towards distance-based fares. Many operators, such as bus operators in Japan, operate non-linear distance based fares. That is, a certain base fare increases per km distance travelled but the marginal increase per km is decreasing. If one applies this to path finding in a network context the fares become "non-additive" as the fare for a specific link will be dependent on a travelers origin. **Fig. 2** illustrates the challenge where $c^x_y$ denotes the cost of link x for traveler with origin y. Assume that the first km is priced 5 units, the 2nd km 3 units and the 3rd km 2 units. Then link BC will cost travelers from A 3 units but travelers from B 5 units. The situation is even more complex for link CD where travelers from A will be charged different for the same link depending on which path they have taken to reach C.

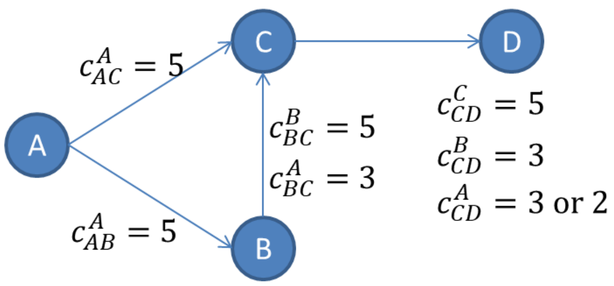


Figure 2. Example network with path-specific link costs

Furthermore, in public transport waiting times have to be considered leading to the notion of "hyperpaths". This can be defined as a set of attractive paths any of which might be optimal and an accompanying strategy to select a path among these attractive paths. Take a traveler at A aiming to go to D and assume all links are bus lines. Now if bus AC is coming s/he should certainly take it, but what if bus AB comes first? If bus BC is frequent and fast, it might be optimal for the traveler not to wait at A for AC, especially if s/he has just missed a connection. Combining these two challenges leads to the operations research problem of finding optimal hyperpaths considering non-additive fares to which a solution has been presented in *Maadi, S. and Schmöcker, J.-D. (2017). Optimal Hyperpaths With Non-Additive Link Costs. Transportation Research Part B, 104, 235-248.*

**Optimal distance-based fares**

The discussion on non-additive fares further leads to the question as to whether such fare structures can lead to "win-win" situations for travelers and the operator in a multi-modal context. In order to show that there are such non-additive fare solutions consider **Fig. 3**. The network includes one origin (node O) and two destinations (nodes 1 and 2). Links are defined by travel time and length, shown in the square brackets in the figure. Links a, b and c are public transport links and induce a fare, whereas d is seen as an alternative mode that is not charged (or the charge is collected by a different, say taxi, operator.) Links a and b are identical, whereas c is longer but faster. The cost is only needed to calculate the fare, therefore the length of link d is irrelevant.

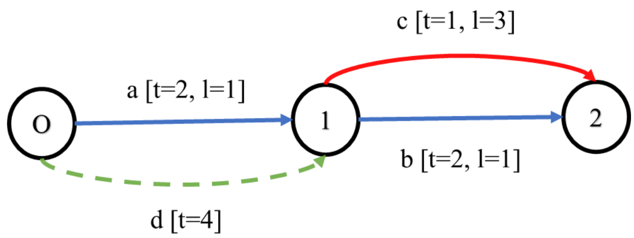


Figure 3. Example multi-modal network

Now with an additive fare structure where all links are charged the same the long, and hence expensive, link c can be unattractive but in a non-additive case c might be become interesting as travelers from O to 2 can obtain discounts for c if they have travelled link a already. On the contrary link a might become unattractive for travelers from O to 1 if the first fare stage becomes too inexpensive. Therefore there are fares that lead to at least the same fare revenue but less travel time than additive fares. For example, for the above example network, one can show that for equal demand from O to 1 and O to 2 a fare of 1 unit per km leads to the same revenue but less travel time as a fare of 1.2 units for the first 1.5km and 0 for any subsequent travel. Thus, given that fast links have some spare capacity, marginally decreasing fares can be optimal from a social utility perspective. Deriving optimal non-additive fare structures is topic of ongoing research.

## 大気汚染物質が人の健康に及ぼす影響の定量化

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### はじめに

日本は戦後の工業化と高度経済成長に伴う公害を克服してきた歴史があります．現在の開発途上国も経済の急成長に伴い，さまざまな環境汚染とそれによる健康被害に直面しています．大気汚染に伴う健康影響は，地域の問題としてだけでなく地球規模の問題です．人間は呼吸をする限りは大気中に存在する汚染物質への曝露（ばくろ）は避けられません．したがって，大気汚染への曝露を減らすためには，個人の努力よりも，地域の大気環境を改善するための法律や規制が必要となります．日本，欧米をはじめとする先進国では，数多くの科学的知見により，「大気汚染は体に悪い」ということが示され，それらの知見をもとに大気質のガイドラインや環境基準が設定されてきました．たとえば，細胞や動物を対象とした実験的研究により大気汚染が疾患を引き起こすメカニズムが解明され，人の集団を対象とした疫学研究が大気汚染への曝露とさまざまな健康事象（疾患の発生や増加，死亡など）との量的関係を明らかにしました．

本稿では，疫学的アプローチを用いた大気汚染物質の健康影響評価に関する研究を紹介します．

### 微小粒子状物質（PM2.5）の健康影響

粒子状物質はさまざまな粒径や組成の粒子を含む混合物で，その組成により物理的，化学的性質が異なります．その発生源は，人為起源と自然起源に大別され，人為起源には，固定発生源（工場・事業場等）と移動発生源（自動車，船舶及び航空機等）があり，自然起源としては土壌の巻き上げや海塩粒子，火山や砂漠由来の粒子が挙げられます．環境大気中粒子の大きさは大小さまざまで，粒径が1～2μm付近に谷を持つ二峰型を示します．この峰のうち粒径の小さい方を微小粒子といいます．PM2.5は粒径2.5μm以下の微小粒子で，粗大粒子に比べて呼吸器系の奥深く（下気道，肺胞領域）に沈着しやすく，粒子表面の有害な成分が吸収・吸着され，より深刻な健康影響が起こることが懸念され，日本では2009年に環境基準が設定されました．

PM2.5や他の大気汚染物質の健康影響を検討する場合には，曝露から健康影響が発現するまでの時間により，概ね日単位の短期曝露と年単位の長期曝露による健康影響に分類することができます．

短期曝露影響は，PM2.5の曝露後数時間から数日以内に起こりうる健康影響（死亡，疾患の発症・増悪，症状の変化）です．疫学研究においては，PM2.5濃度と死亡数，入院数や症状の変化などの健康事象の時間的変動を比較することにより関係性を明らかにします．PM2.5の濃度や健康事象は，他の要因（交絡因子といいます）の影響も受けるため，それらを考慮する必要があります．たとえば，ある地域における日々の急病による救急搬送数とPM2.5濃度（図1）と

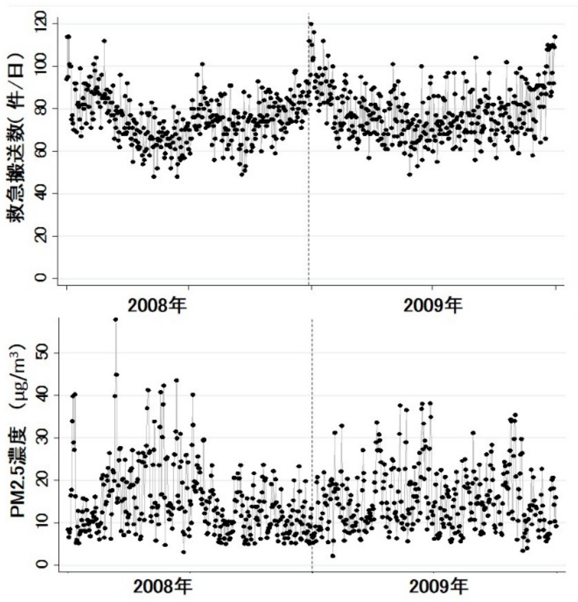


図1　ある地域における日々の急病による救急搬送数（上図）とPM2.5濃度（下図）の推移．救急搬送数は冬に多く夏に少ない季節変動がある．

の関係を例にとると，これらは季節や曜日により変動することが知られていますし，気象条件の影響を受けるため（図2），救急搬送数とPM2.5濃度との関係性は見かけ上歪んで見える可能性があります．しかし，このような交絡因子をうまく考慮した統計解析をすることにより，PM2.5の増加と急病（特に呼吸器疾患など）の増加との関係が観察されるのです[1]．

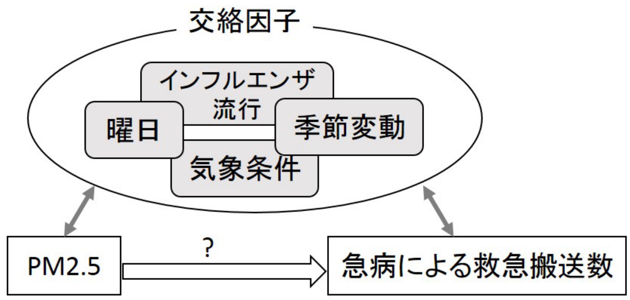


図2　PM2.5と急病による救急搬送と交絡因子

一方，長期曝露影響は，PM2.5と健康事象の空間的な変動に着目します．たとえば，異なるPM2.5濃度レベルの地域に住んでいる人々を長期間追跡し，新たな疾患の発生や死亡の発生を観察するコホート研究では，PM2.5の濃度の高い地域に住む（PM2.5曝露レベルが高い）人々の方が，濃度の低い地域に住む人々よりも死亡する確率が高いかどうかを観察するわけです．もちろん，人の死亡は大気汚染だけではなく，性別，年齢，喫煙習慣の有無，高血圧・糖

尿病といった疾患の有無など，さまざまな交絡因子が関わります．このようなコホート研究では，研究開始時点で交絡因子の情報も集めて，それらを考慮した解析を行います．1974年から始まった宮城県，愛知県，大阪府における都市地区と対象地区，6地域の40 歳以上の住人を追跡した三府県コホート研究では，PM2.5 濃度が10 μg/m$^3$上昇することにより肺がん死亡が22%増えることが観察されました[2]．

### 地球規模でみたPM2.5関連死亡数

上記の疫学研究で得られた結果からPM2.5と健康影響の関係を示す関数を構築し，地域のPM2.5濃度の情報を組み合わせることにより，PM2.5により損なわれたであろう人々の健康の程度（疾病負荷）を，PM2.5関連死亡数として推定することができます．この疾病負荷の情報は，他の要因による疾病負荷と比較して政策の優先順位について検討したり，特定の政策をした場合にどの程度の死亡や疾患が予防できるかという健康インパクト評価にも用いられます．まず，PM2.5と死亡との関係を示す関数を構築するために，過去に行われたPM2.5と死亡との関連について調べたコホート研究25件の結果を抽出しました．その研究が行われた地域の平均的な濃度と，基準となる地域と比較した場合の死亡確率の割合（相対リスクといいます）をグラフに示したところ，研究にばらつきはあるものの，濃度が増えるほど相対リスクが高くなることが示されました[3]（図3）．PM2.5の年間平均濃度が50μg/m$^3$を超える高濃度地域からの研究結果は現在のところ報告されていないため，PM2.5濃度と死亡との関係は線形であると仮定しました．次に，このPM2.5-死亡関数と数値モデルで推定された2010年のPM2.5濃度，各国の死亡数（人口と死亡率により算出される）を用いることにより全世界のPM2.5関連死亡数を推定しました．PM2.5関連死亡数は，年間数百万人にのぼり，特にアジア地域での関連死亡数が多いことがわかりました（図4）．

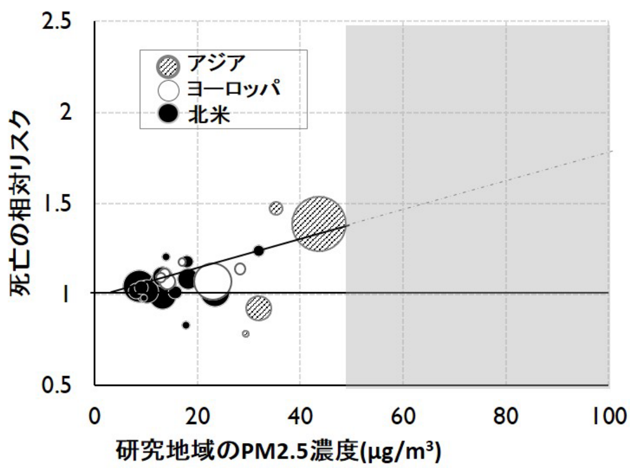


図３　研究ごとのPM2.5濃度と基準となる濃度（人為由来排出源がないと仮定した場合の濃度，ここでは5.8μg/m$^3$としている）での死亡リスクと比較した相対リスク．研究規模が大きいほど，円が大きい．）年間のPM2.5濃度が50μg/m$^3$超える地域（グレーの部分）での研究結果は今のところ報告されていない．

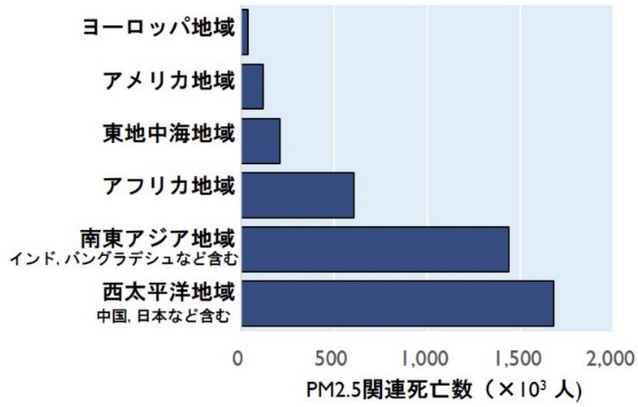


図４　地域別PM2.5関連死亡数

### 疫学研究に関する不確実性

図3に示されたように，PM2.5と死亡との関係は一定の傾向はあるものの，地域や研究によりばらつきがあります．このばらつきはどこに由来するのでしょうか．そもそも疫学研究では集団を対象としているため，研究間のばらつきには個人の感受性，生活習慣の違いが関わっているかもしれません．たとえば，高齢者は大気汚染の影響を受けやすいと言われているため，高齢者の多い地域では見かけ上，関連が強くみられるかもしれません．また，PM2.5はさまざまな粒子成分を含むため，その成分の違いが関連の強さを変えている可能性もあります．疫学研究はあくまで関連性を見ているだけであり，得られた結果だけで因果関係があるという結論をすることはできません．メカニズムを明らかにする毒性学的研究の結果も含めて総合的に判断することが必要です．

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