Monitoring catastrophic ground collapse of urban roads with permanent curbside electrode arrays

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Abstract. Active underground constructions and leaking utility pipelines in urban areas can seriously undermine the foundation of roads. Deadly collapse of road surface may suddenly happen if the soil under pavement is washed away. This paper proposes a permanent and economical monitoring approach based on the electric resistivity method. By exploiting the intrinsic volume effect in electric exploration, electrode arrays installed on curbside can be used to detect developing cavities beneath road surface. I present a fast survey scheme with the ability of focusing current paths on high-risk areas. This new method is numerically tested on some synthetic resistivity models that are snapshots of randomly-grown cavity at a road intersection. The modelled data show that decent data anomalies can be measured at favorably-coupled electrode positions, and the daily variation of the acquired electric field data may forecast the critical moment of pavement failure. The numerical results encourage further field work to be carried out to validate this curbside monitoring idea.

1. Introduction
Sudden collapse of road surface as the result of displaced soil (e.g. removed by groundwater or water from leaking pipes) has become one of the most horrifying urban geo-hazards in many cities, because it randomly kills people in streets with no warning and no time of escape. For example, on December 1, 2019, a massive collapse took place at a busy intersection in the megacity Guangzhou, killing 3 in seconds. Little more than a month later, another road surface collapse destroyed a bus killing 10 and injuring 17 in a capital city of western China. All incidents happened all of a sudden without any visible or sensible signs for people to take precautions, although the cavities beneath the pavement were already fatally large. Therefore, civil services demand a tool to permanently monitor and quickly forecast potential ground collapse that could be happening in any minutes.

Drilling is critical in confirming and treating cavities, but not practical in monitoring on a daily basis. Vehicle-mounted geo-radar (or GPR) scanning is a high-precision technique for the detection of defects under pavement [3], but is labor intensive and the revisit time may be beyond the time scale of cavity growth. InSAR may be useful in detecting the subtle surface deformation [2], but its effectiveness can be hampered by long revisit times and block of view in urban areas. Other geophysical methods, like microgravity and active source seismic, are good options in one-time focused investigations at chosen sites [6], but are not feasible in continuous monitoring on open roads with heavy traffic. The air-filled cavities contrast the surrounding soil in electric conductivity significantly, so electric or electromagnetic (EM) methods are also viable choices, and successful applications have been reported in solving similar problems [1,5].
Electric methods are particularly suitable for monitoring road surface collapse. Firstly, the EM environment on urban roads can be extremely noisy, and the noise can swamp or coherently contaminate weak EM signals from cavities. Electric methods only use the steady-state portion of the EM field, so they are much more reliable in such complex EM environment. Secondly, EM methods often require large open space to deploy bulky instruments, loops and sensors, but such site conditions are difficult to satisfy on urban roads and not practical for permanent monitoring. Electric methods in its simplest form only require steel rod electrodes installed and simple cables connecting the electrodes; they take very little space. Lastly, because of the system simplicity, electric instruments are much cheaper to install and much easier to maintain than EM, making it the best candidate as a permanent monitoring tool.

Therefore, this paper proposes a novel curbside electrode array system for the collapse monitoring problem. Without any installation on the road surface, this new approach has minimum interference to traffic and the electrodes and cables are not subject to wear and tear by vehicles. In the following, I show that, although not directly above the cavity like the conventional arrays, such a curbside array can still be sensitive to the growth of cavity if a special survey scheme and a focusing data processing method are carried out. The present research is theoretical and hypothetical, but I hope that this idea can inspire initiatives that install sensing "nerves" in the streets to support the building of smart cities.

2. Survey Configuration

2.1. Curbside electrode arrays

Conventional dc resistivity surveys place electrodes as directly above the target as possible. However, in the application discussed here, the dangerous cavities are often beneath the road pavement and installation of monitoring electrodes and cables directly on the road surface is impossible. The next feasible space on and near city roads is curbside because there is often exposed soil for electrode grounding and more space for cabling. Curbside electrodes are also less likely to interfere with the business on sidewalk at commercial areas.

Our approach proposes to continuously install long electrode spreads along street curbs at a spacing of a few meters (Figure 1). The conventional electric systems gather cables from electrodes in a central switch box or console, but this mechanism does not work for a distributed monitoring system.
across multiple street blocks or even the entire city. For such a monitoring system, it is better to group every 10 or 20 electrodes on one side of curbs into one module; every module is wired together and commanded and logged by a module console; the cities then orchestrate multiple consoles according to a predefined scheme so the transmitting and measuring can happen concurrently in different modules.

2.2. Survey scheme

Conventional dc resistivity methods utilize a variety of array configurations to achieve different exploration goals, for example, Wenner, Schlumberger, dipole-dipole, pole-dipole, pole-pole, etc. Because curbside electrodes are subdivided into modules, the conventional configurations are difficult to implement. Instead, I propose to use an extended pole-pole (or A-M) survey scheme orchestrated by an inter-modular controller. In this scheme, electrodes take turns to act as the source electrode (A) with the return electrode (B) at infinity. When an electrode is transmitting current, other electrodes in the same module together with the electrodes in all other modules act as the potential electrode (M) with the other potential electrode (N) at infinity. Once all possible A-M combinations are measured, data from any arbitrary configuration of ABMN can be obtained by sign reversal, superposition and differentiation.

In my synthetic example of numerical modeling, two 20-m wide roads intersect and a round-shaped sinkhole develops at the center of the intersection. Curbside electrodes for this intersection numbered 1 to 84 are deployed as shown in Figure 2. For such a cavity, the pair of current electrode No. 11 and No. 53 would have the maximum excitation (green line). To achieve the equivalent effect, data from when No. 11 is transmitting and data from when No. 53 is transmitting are sign reversed and summed up. There is no potential electrode above the cavity, but the pair of potential electrode No. 31 and No. 33 is oriented in a favorable direction to capture the anomalous electric field from the cavity (blue line). Other combination and superposition of data can also be computed depending on which part of the road is of particular interest. It is important to note that only the simple pole-pole (A-M) survey is carried out in the field, and the derived data for interpretation can be quickly obtained through data processing on computers. Therefore, the revisit time of time-lapse monitoring at such an intersection can be at the scale of minutes, providing high time resolution.

Figure 2. Synthetic curbside electrode configuration for the monitoring of collapse at a road intersection
3. Numerical Simulations

3.1. Random growth model of cavity
The shape of most cavities in ground collapse depends on many geotechnical conditions and is not regular. In order to more realistically simulate the development of cavity, I designed a random growth model. The earth is first discretized into cubic cells in a 3D mesh. A few cells 9 m below the surface at the center of the intersection (leak point) are designated as air-filled at the very beginning. At each time step, every air-filled cell can cause one of its six surrounding cells to collapse (i.e. become air-filled). Based on geotechnical experiments [4], the probability of causing the cell above to collapse is the highest, the cells on side are intermediate, and the cell below is the lowest.

In the current implementation, the development of a cavity during a course of 30 days is simulated at a time step of one day for the purpose of demonstration (Figure 3). The initial status assumes the soil below the pavement is a uniform half-space of 50 Ωm. The cavity expands in all directions, but grows upwards more quickly. On Day 19, the top of cavity reaches the surface; on Day 22, significant area of pavement is not supported by any soil; the ground collapse could happen at any time from Day 19 to Day 22. From Day 22 onward, the growth simulation continues, but those models are not likely to exist in reality as the cavity's horizontal extent becomes too large.

![Figure 3. Development of an air-filled cavity under a road intersection](image)

3.2. Anomalous data in electric field
The proposed new survey scheme with the 84 curbside electrodes is numerically simulated for the 30 cavity models using the 3D algorithm in Yang et al. [7]. Then the data are processed to obtain the equivalent datum as if the current electrodes are No. 11 and No. 53 and the potential electrodes are No. 31 and No. 33 in Figure 2. In principle, this particular combination of current and potential electrodes has the strongest response to the cavity at the intersection center.

In the first few days, there is no obvious change in the measured potential difference between the electrode No. 31 and No. 33, when the cavity is still small and deep (Figure 4). As the cavity expands and grows towards the surface, the increase of measured potential difference speeds up, as a result of increased area of the cavity-soil interface and more electric charges built up on that interface. The measured potential difference keeps increasing, but the daily variation peaks at about Day 22, consistent with the previous forecast that the road may collapse before Day 22. After Day 22, the
cavity can only grow horizontally, so the speed of increase declines. Although the models after Day 22 may not practically exist, a downturn in the daily variation plot, if observed, may indicate that a collapse is overdue, and the roads need to be checked or treated immediately.

The analysis presented here is at a hypothetical time scale of days. Since the revisit time of this curbside monitoring system is about minutes, it is all possible to carry out similar analyses at the scale from minutes and hours to months and years. The potential applications may include both collapse early warnings for emergency evacuation and seasonal geo-hazard risk assessments.

Figure 4. Potential difference and its daily variation measured across the electrode No. 31 and No. 33 during the growth of cavity in 30 days. The data are normalized by the source current strength.

4. Conclusions
A novel electric monitoring system is proposed to provide evidences for the forecast of deadly ground collapse on urban roads. Instead of deploying the electrodes on the road surface and above potential cavities, the system relies on continuous electrode arrays along road curbs. Such permanent curbside arrays have great advantages in its simplicity, durability and reliability. I also design an extended pole-pole survey scheme for modularized curbside arrays that is both fast and versatile – arbitrary electrode configurations can be generated by a linear combination of the original pole-pole data.

The idea above is numerically tested on a cavity-under-intersection model. The cavity, simulated by a random infection approach, gradually grows from a negligible volume at depth to a large hole invading the pavement. This process is captured by the curbside electrode arrays and reflected as an increase in the measured potential difference data. Further analysis indicates that the speed of change of those data is a good forecast of collapse that is either at high probability or already overdue. The next necessary step is field experiment that verifies whether the estimated amplitude of data anomaly can be practically measured in typical urban road environments.

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