Assessment of Air Pressure inside a Drainage Stack

Eric S. W. Wong, Daniel W. T. Chan, Phil Jones and Leo K. C. Law

***Abstract*—After the outbreak of 2003 SARS in Hong Kong, drainage has been considered as a path of virus transmission. When the floor trap has no water seal, smell can come through the drainage pipe. Loss of water seal of the trap can be caused by excess air pressure within drainage pipe especially in the stack of drainage. It is very difficult to make assessment on air pressure profile within stack and a prediction model is required. In this paper we will review and develop assessment models using experiment method. Partial differential equations predicting the air pressure profile within stack are used. The pressure profile shows positive and negative air pressures zones with respect to heights of discharge points, which are key elements to form a drainage monitoring system of a real building. A risk assessment protocol is developed to monitor the degree of water seal oscillation**.

***Index Terms*—air pressure profile, building drainage system, one dimension one phase flow, trap seal oscillation, two dimensions two phases flow.**

I. Introduction

In Hong Kong, many high-rise buildings have problems in drainage system. Most of the aged pipes and stacks are suffered from scaling problems, leading to blockage inside the pipe, and results in an increase of the air and water pressure. This would cause leakage problem if the discharge rate increase, with a decrease in internal diameter due to scaling. Different from other building services system, for example the air-conditioning or electrical system with a number of options of monitoring device and computerized control, there is a lack of detection devices suitable for drainage system performance monitoring.

The importance of a well-performed drainage system on protecting public health was not attentive until the outbreak of Severe Acute Respiratory Syndrome (SARS) in 2003. The SARS outbreak incident tells us that drainage system does have an influence on the health and safety of residents.

It was realized that the good practices of design, operation and maintenance of the drainage system is an important issue. The consequent imposed to building users, due to problematic drainage system, is not solely confined to complaints on fouls smell alone but more seriously the dispersion of bacteria and virus, causing sickness, or in the most serious scenario, fatalities. To safeguard building occupiers' health and life safety, and to help the building maintenance engineers who are looking for a user-friendly monitoring of the quality of drainage system, the development of an automatic detection system is necessary, such that building users and engineers can spot out any defect or blocking of the aged drainage pipe easily.

Figure 1 Scaling of the aged drain pipe

II. Parameters for Monitoring

A well-performed drainage system should be able to convey the soil and waste matter fluently to the designated location such as a manhole or a sewer. Any blockage in the pipework results in an increased air and water pressure. From this consideration, the degree of the fluctuation of the pressure inside the piping system can be a good indicator of the fluency of soil and waste discharge. The field measurement results can also be calibrated and validated by a simulation model. In addition, the everyday maintenance on the drainage system can be performed better by initiating acupuncture study, signal levels analysis and establishing an alarm system of the building drainage.

An acupuncture study on drainage system helps in the selection of the representative locations of stack pressure monitoring. Drainage problem include blockage, noise, vibration, loss of water seal, smell emitted. All of them are related to the variation of pressure transient.

Air pressure transient propagation within the above ground building drainage and vent systems should show positive or negative pressure changes in response to decelerating or accelerating flow conditions. Positive pressure transient typically occurs near the bottom-most turning point of the stack, while the maximum pressure depends on the height of the stack, the design and connection method of ventilation stack to the discharge stack, stack cross-sectional diameter and the discharge loading. Negative pressure transient profile of a drainage stack is influenced by the drainage network; for different individual drainage stack it should have its own negative pressure transient. The concept of the reduction on

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trap seal levels by induced siphonage, due to negative pressure transients, is well understood in the study of building drainage system. The more problematic issue on pressure transient in a vertical drainage stack is the propagation of positive air pressure transients, generated by stack or branch surcharge, since it can result in a broken-out of trap seal water and flow to the occupied room, and also results in contamination due to bubbling through the trap under positive pressures. As a result, a recommendation on the priority of air pressure sensors installation shall be, the bottom of the stack should be allocated with a sensor at a highest priority, and the next location for continuous monitoring would be, the height level with highest negative air pressure. This height level can be performed by a cross-sectional measurement at various floors along the stack, or estimated by computational simulation models.

III. Review on simulation models

Several simulation models for the determination stack pressure profile are available, for example, the one developed by Herriot Watt University (HW), the National Taiwan University (NTUST), or using a computation fluid dynamics (CFD) simulation program. The simulation model by Herriot Watt employs a finite-difference technique based upon the definition of propagation of air pressure transients using the St Venant equations of continuity and momentum.

A. St Venant Equations

The equations of continuity and momentum applicable to a full-bore flow element of air within a drainage system may be shown to be,

Continuity:

$$\frac{\partial \rho}{\partial t} + \rho \frac{\partial u}{\partial x} + u \frac{\partial \rho}{\partial x} = 0 \qquad \text{(eq. 1)}$$

Momentum:

$$\rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial x} = -\frac{\partial P}{\partial x} + \frac{4\rho f |u| u}{2D} \qquad \text{(eq. 2)}$$

Where ρ is density of air, x is displacement, u is air velocity, D is diameter of stack and f is function of location, discharge variables. It is for the prediction of drainage stack pressure profile. Using grid method, different boundaries and conditions have been set up for calculation (Figure 2).

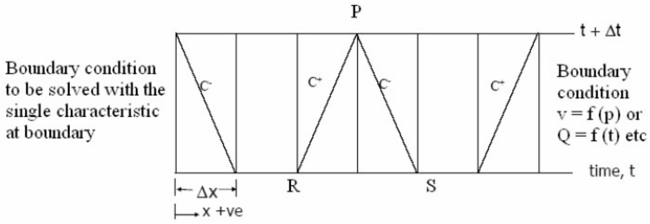

Figure 2 Set up C+ and C- equations and solve by different boundary conditions.

For the case of low amplitude air pressure transient propagation, they may be expressed as,

$$c\frac{\partial u}{\partial x} + \left(\frac{2}{\gamma - 1}\right)\left[u\frac{\partial c}{\partial x} + \frac{\partial c}{\partial t}\right] = 0 \qquad \text{(eq. 3)}$$

$$\left(\frac{2}{\gamma - 1}\right) c\frac{\partial c}{\partial x} + u\frac{\partial u}{\partial x} + \frac{\partial u}{\partial t} + \frac{4f|u|u}{2D} = 0 \qquad \text{(eq. 4)}$$

These relationships are a pair of quasi-linear hyperbolic partial differential equations that are amenable to finite differential solution once transformed via the method of characteristics into the finite difference relationships represented by Eqs. (3)-(4) that link condition at a node one time step in the future to current conditions at adjacent upstream and downstream nodes.

For the C^+ characteristic

$$u_P - u_R + \frac{2}{\gamma - 1}(c_P - c_R) + \frac{4 f_R |u_R| u_R \Delta t}{2D} = 0 \qquad \text{(eq. 5)}$$

when

$$\frac{dx}{dt} = u + c \qquad \text{(eq. 6)}$$

and for the C^- characteristic

$$u_P - u_S - \frac{2}{\gamma - 1}(c_P - c_S) + \frac{4 f_S |u_S| u_S \Delta t}{2D} = 0 \qquad \text{(eq. 7)}$$

when

$$\frac{dx}{dt} = u - c \qquad \text{(eq. 8)}$$

where the wave speed c is given by

$$C = \sqrt{\gamma p / \rho} \qquad \text{(eq. 9)}$$

(Note: f_R and f_S are functions of time, location and annular water down flow.)

The relationships of air pressure and wave speed c is

$$p_{local} = \left[(p_{atm}/\rho_{atm})(\gamma / c^2_{local})^{\gamma}\right]^{1/(1-\gamma)} \qquad \text{(eq. 10)}$$

Boundary conditions must be provided for different ends and branches of stack. Pressure values can be found along the stack. Height of pressure point can be found by solving dx/dt. However, the model is mainly focus on the flow of air.

B. NTUST Model

Another simulation model developed by NTUST adopts the equations by means of regression method, based on field experiment data. The National Taiwan University (NTUST) prediction model defines four zones, which comprise the overall pressure response of the system subject to steady water inflow. These four zones are: pressure loss in the dry stack; the concentrated pressure loss generated at an active branch connection; pressure regain in the constant (water down-flow) velocity section of the wet stack; and positive pressure as the entrained airflow is impeded at the stack base before recovering to atmospheric in the sewer connection pipework.

This prediction model uses regression functions operating on stack height and discharge flow rate, of 'reduction ratios' in peak pressure predictions. These ratios are based upon a comparison of maximum pressure levels within vented networks with those measured when the stack is curtailed to represent a single stack system. It was found that reduction ratios were more readily identified for peak negative pressures, whereas those for positive pressure, it demonstrates a significant degree of variability. The model uses a flow rate which was estimated from discharge unit from sanitary appliance, and discharge flow rates have considered the probability of usage. C_2, d_2, i_2 and q_1 are experiment coefficient. FL is discharge height and Q_w is flow rate.

$$P_i = C_2 \times (FL \times Q_w)^{d2} \quad (11)$$

$$P_B = i_2 \times (FL \times Q_w)^{j2} \quad (12)$$

$$P_D = p_1 \times (FL \times Q_w)^{q1} \quad (13)$$

$$P_{neg} = P_i - P_D \quad (14)$$

$$P_A = P_i - P_D - P_B \quad (15)$$

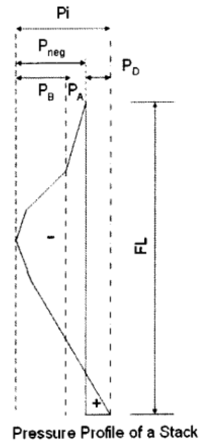

Figure 3 Computation approach of the NTUST simulation model

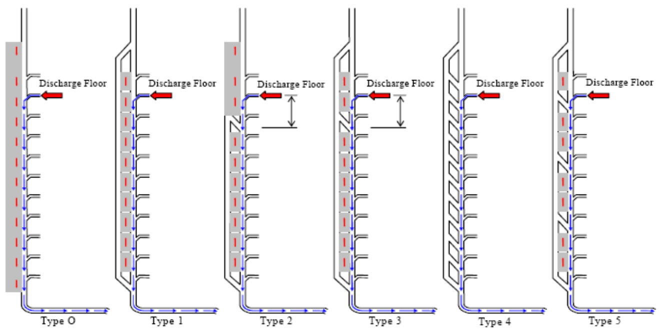

Figure 4 Different ventilation conditions in the NTUST model

C. VOF Model

In addition to the above-metioned models, one may establish a model which directly applies a set of Volume Fraction Equations (VOF) for simulation. The tracking of the interface(s) between the phases is accomplished by the solution of a continuity equation for the volume fraction of one (or more) of the phases. For water, this equation has the following form:

$$\frac{\partial}{\partial t}(\alpha_w \rho_w) + \nabla \cdot (\alpha_w \rho_w \vec{v}_w) = 0 \quad \text{(eq. 16)}$$

For air,

$$\frac{\partial}{\partial t}(\alpha_a \rho_a) + \nabla \cdot (\alpha_a \rho_a \vec{v}_a) = 0 \quad \text{(eq. 17)}$$

The volume fraction equation will not be solved for the primary phase (in our case, the primary phase is air); the primary-phase (air) volume fraction will be computed based on the following constraint:

$$\alpha_a + \alpha_w = 1 \quad \text{(eq. 18)}$$

The properties appearing in the transport equations are determined by the presence of the component phases in each control volume (cells). In a two-phase system with air-phase and water-phase, the density in each cell is given by

$$\rho = \alpha_a \rho_a + \alpha_w \rho_w \quad \text{(eq. 19)}$$

A single momentum equation is solved throughout the domain, and the resulting velocity field is shared among the phases. The momentum equation as shown below, is dependent on the volume fractions of all phases through the properties ρ and μ.

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v}\vec{v}) = -\nabla p + \nabla \cdot \left[\mu\left(\nabla \vec{v} + \nabla \vec{v}^T\right)\right] + \rho \vec{g} \quad \text{(eq. 20)}$$

One limitation of the shared-fields approximation is that in cases where large velocity differences exist between the phases, the accuracy of the velocities computed near the interface can be adversely affected. The problem can be solved by the use of Euler Explicit Scheme.

Euler Explicit Scheme is used for the calculation of face fluxes (convection and diffusion fluxes through the control volume faces) for the VOF model.

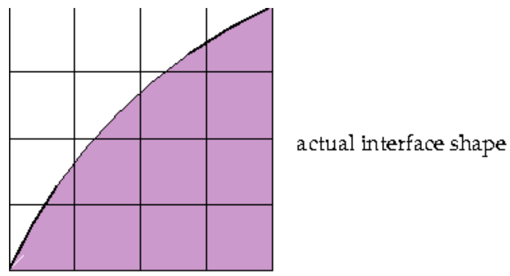

Figure 5 Euler Explicit Scheme

In the Euler explicit approach, standard finite-difference interpolation schemes are applied to the volume fraction values that were computed at the previous time step.

$$\frac{\alpha_a^{n+1}\rho_a^{n+1} - \alpha_a^n \rho_a^n}{\Delta t} V + \sum_f \left(\rho_a U_f^n \alpha_{a,f}^n\right) = 0 \quad \text{(eq. 21)}$$

Where

n+1 = index for new (current) time step

N = index for previous time step

$\alpha_{a,f}^n$ = face value of the air volume fraction, computed from the Modified HRIC scheme

V = volume of cell

U_f = volume flux through the face, based on normal velocity

With the use of Computational Fluid Dynamics (CFD) program developed by Fluent, Inc, a simulation can be performed on a full-scale vertical drainage stack experimental set-up with 7m height (approximately 3-storey), pipe size 200mm diameter, and 100 mm diameter for branch pipes respectively. Water flow at a velocity 1m/s from branches is specified. The air and water velocities inside the drainage stack is shown in figure 6.

In our calculation, atmosphere pressure is assumed to be 101325 Pa; gravity acceleration velocity $g = 9.81m/s^2$; flow is unsteady flow which is variable with time. Moreover, simulated flow is turbulent simulation (standard k-epsilon model) applied with near-wall treatment and use standard wall functions method. Now simulation is made for two phases (air and water) in the stack.

The pressure profile shows positive and negative pressure zones inside the drainage stack (figure 7). Pressure inside the stack is varies with the height of stack. By this simulation, the height levels of maximum and minimum pressure, and their magnitude, can be identified. Figure 8 shows the velocity profile inside the stack.

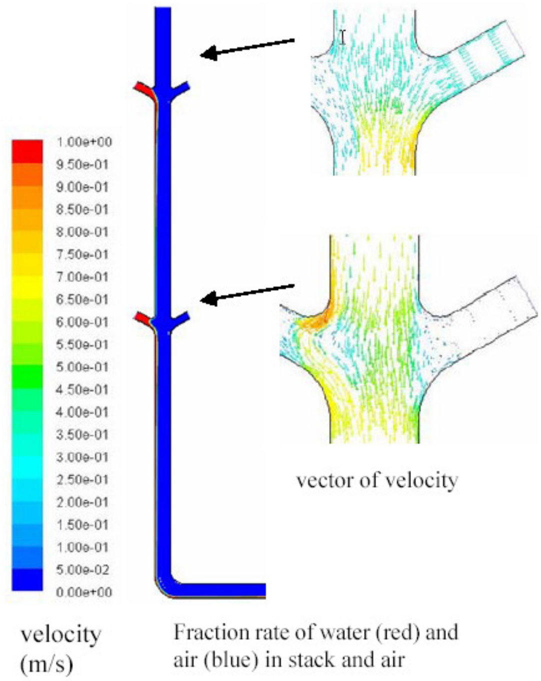

Figure 6 CFD simulation result

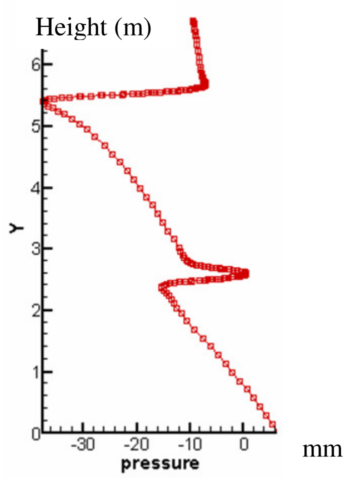

Figure 7 pressure profile of stack

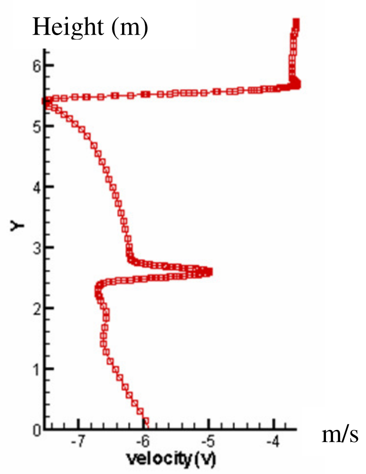

Figure 8 velocity profile of stack

IV. VERIFICATION BY SITE MEASUREMENT

The simulation model can be verified by field experiment. The experiment was performed in Block M of the Hong Kong Polytechnic University with 18 storeys. The prediction of stack air pressure was performed with the use of the NTUST model and the field experiment data measured along the drainage system. By disaggregating the datasets, this examination the numerical modeling components can be evaluated. This serves for an accurate prediction of system air pressures.

Water was discharged from water tap on sink and basin to the drainage system, and the discharge flow rate was measured by flow meter cup for each water tap. Stack air pressure was measured by pressure sensor mounted on the stack at M/F.

In NTUST model, the air pressure profile was simulated with the use of Type 5 ventilation configuration of drainage stack (i.e. the moderate vented design) with four different water discharge flow rates (0.33 – 1.46 litre/second) from 9/F. Pressure drops from the atmospheric level, at a location of the upper stack entry due to friction and the suction effects of air through the water curtains formed at discharging branch junctions. Air pressure profile in stack represents a typical case for a drainage stack carrying an annular water down-flow. At the lower part of the discharge stack, the pressure recovers to a level above atmospheric and demonstrates the establishment of a positive backpressure due to the traction forces exerted on the airflow prior to falling across the water curtain at the stack base.

The typical discharge flow rate for this office building is based on the IPHE method. IPHE method considers the frequency of usage, and the selected discharged rates for our study are within the range of utilization.

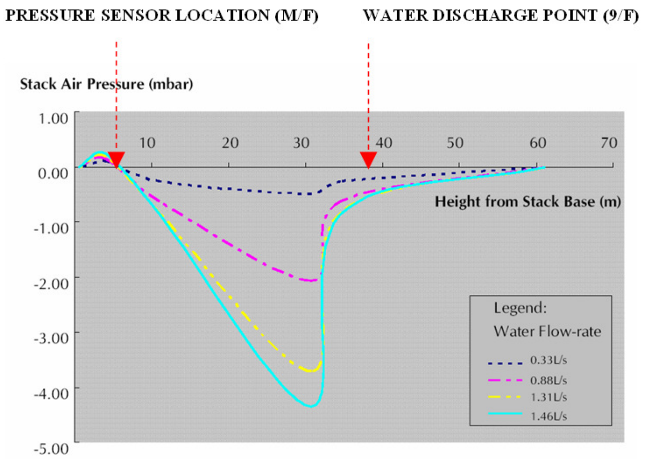

Figure 9 Air Pressure profile in Stack at Block M

Figure 9 presents the air pressure prediction made from the National Taiwan University (NTUST) simulation model with selected flow rates. In simulation, it selects the ventilation configurations (through adaptation of the stack and referred to as Types 5), four discharge flow rates (0.33 – 1.46 litre/second) and one input level (9/F at a height of 34.5m above the stack base).

For the drainage stack installed in our case study building, the high negative pressure zone was located at a height of 28m above the stack. The location between the fifth floor and the seventh floor is appropriate for the air pressure sensor installation, to monitor the variation of negative pressure.

The positive pressure monitoring point is located at 1/F of the case study building, which is near to the bottom base of the vertical drainage discharge stack. From the results of measurement at M Block, Fig 10 shows the comparison between predicted stack air pressure and the measured value at the positive pressure location.

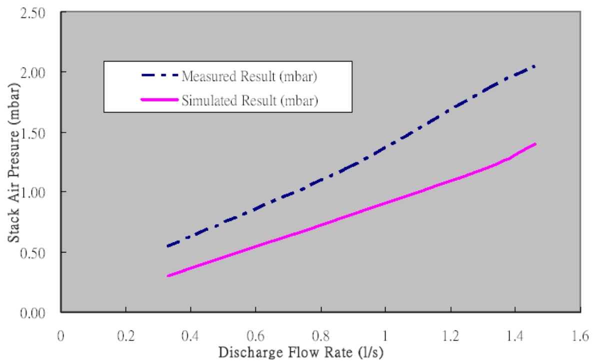

Figure 10 A comparison on the air pressure transient propagation between observed and simulated results at the measurement point (M/F)

V. Accuracy of Selected Model

Based on our result shown in figure 11, the NTUST simulation appears to underestimate the pressure induced in the bottom part of the stack region. It should be aware that the data is representative of steady-state conditions for a specified water down-flow and a single point discharge. Recent research conducted by Herriot-Watt shows that the intermittent behavior of the water curtain formed at the stack base results in an impediment to entrained airflow such that positive air pressure transients are propagated upwards through the network. These short-duration peak pressure levels are often difficult to monitor and are often obscured by lower magnitude steady-state measurements.

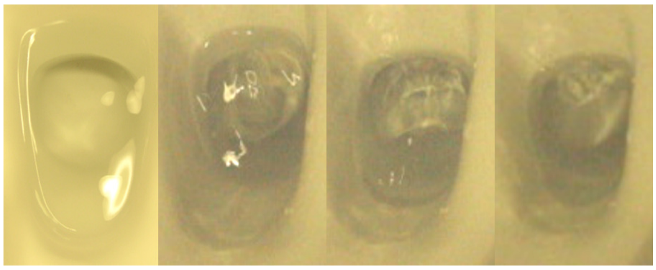

Figure 11 Trap seal oscillation (from a stationary state to the establishment of air bubble path)

Figure 11 shows that one of the water closets at the lower floor (1/F, near the bottom turning point of the drainage stack) suffers from pressure transient when the stack air pressure reaches at high level of negative pressure. This indicates the selected discharge rates for our investigation matches with the observed scenario.

VI. Detection Scale of Monitoring Levels

A. *Air Pressure variation inside stack*

The pressure variance in the stack can be detected directly by measuring air pressure by the sensors, and observation on trap seal. Negative pressure in stack results in a suction of trap water seal. Positive pressure in stack would lead to blow-out of trap seal. From our experiments, it is observed that the oscillation of trap seal on appliances is affected by pressure variance and depth of the original depth of trap water seal filled-in. According to local regulations the depth of water seal has to be maintained at 50mm. In our study the observed depth of seal for the water closet at 1/F is under a variance above ±40mm, in this situation the trap seal is regarded as broken. Table 2 suggests the interpretation on the status of the water seal, based on the measured result from continuous monitoring instruments.

Level of concern	Detected air pressure	Amplitude of water seal oscillation	Interpretation
1	Absolute value below 2 mbar	Less than 20 mm	Alarm level
2	Absolute value between 2 to 4 mbar	Between 20mm to 40mm	High risk of broken water trap seal
3	Absolute value above 4 mbar	More than 40mm	Broken trap seal

Table1 Pressure level for monitoring and interpretation of water seal status

B. *Air Pressure variation inside stack*

Beside the effect of pressure variation, water evaporation and the wind effect can also lead to a loss or damaging of water seal. On the risk of water seal loss in traps due to evaporation, when the flat was temporarily unoccupied, two different levels of concerns are recommended. The first level of concern refers to the situation when water has not been used for a period more than 25 days. If water has not been used in a flat for a period more than 40 days, it is highly

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recommended to refill the water trap.

VII. Conclusion

Three pressure prediction models are compared. Equations 1 to 10 are one dimension and one phase flow, St Venant equations are employed. It only considers air pressure transient inside the stack. Equations 16 to 21 are 2 dimensions and 2 phases flow in the stack. Volume Fraction Equations are used. 2 phases conditions are much complicated than one phases and iteration need longer time. Correct boundary conditions should be provided for models to get correct air pressure prediction of the stack. NTUST run a large batch experiments in different drainage systems. Regression method is used to find out coefficients (C2, i2, P1, d2, j2 q1) of experimental equations from 11 to 15 Different vent type has different coefficient which obtained by regression.

This study demonstrates how the status of a building drainage installation can be predicted through simulation models with the calibration by field measurement data, and the monitoring of positive and negative air pressure within the vertical drainage stack.

Air pressure monitoring and inspection of drainage stacks should be emphasized in the agenda of the operation and maintenance practice of existing buildings, in order to enhance the health and safety protection to building occupants.

Acknowledgment

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