Construction solid waste landfills: risk assessment and monitoring by fibre optic sensing technique

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ABSTRACT
The development of underground spaces generates large amounts of construction wastes, which are generally disposed for the landfill outside of the city in China. This study briefly reviewed a landslide tragedy of a CSW landfill in China; Lessons learned from the failure of risk assessment and preventions were discussed, which showed that two challenging strategies are significant for the risk identification and mitigation. One is the effective early warning system based on field large-deformation measurement; the other is the efficient risk assessment with internal deformation data. To this end, a new sensing method is developed for the large-deformation measurement inside CSW landfills. The proposed fibre-optic based transducer can measure large deformation of up to 1200 mm with a high accuracy. Finally, the risk assessment of CSW landfill was proposed with the combined use of field monitoring data and risk evaluation model. The theoretical equations for stability analysis and potential application framework for the application of this technique in the risk assessment of CSW landfill landslide are presented. This approach possesses the advantages of capturing excessive and irregular deformation of solid waste landfills and of efficient response for the risk mitigation with the help of early warning system.

1. Introduction
With the accelerated urbanization process, the rapid expansion of urban population has led to urban traffic congestion, leading to great demands for urban underground space utilization, especially for the subway constructions (Lavigne et al. 2014; Stark et al. 2000; Matura et al. 2010). Taking China as an example, the operating mileage of urban rail transit increased rapidly since 2005. By the end of 2017, a total of 165 urban rail transit lines with an accumulated length of 5033 kilometres in mainland China were constructed. Among them, the subway tunnels reach to the length of...
3884 kilometres (Zhang et al. 2020; Nika et al. 2020). The blooming subway constructions and other underground space developments, such as comprehensive underground pipelines, underground shopping malls, basement parking spaces and deep foundation excavations have posed a challenge with regards to the disposal of a great deal of construction wastes such as concrete, discarded rock/soil mass and residual mud (Nikulishyn et al. 2020; Rao and Ravi 2014; Rao and Ravi 2013; Xu et al. 2020a).

Given the high transportation cost and limited market price of recycled products, in many cases the construction solid or sludge wastes have to be dumped to low-lying land and ponds or used as backfill material in roads, backfill of piles or offshore regradations (Ravi and Rao 2013; Xu et al. 2019b; Iyer et al. 2019; Xu et al. 2020b). Apart from the above solutions, many facilities were established to receive and dispose wastes, providing a new way for re-utilization of construction solid waste (CSW). However, the rapid urbanization in developing countries generates construction wastes at a magnitude that is far more than the re-cycled limits. Thus, many of them have to be long-distance transported and dumped to the specified construction land or abandoned quarries which are normally exploited as the site of CSW landfill.

Every year, there are at least tens of accidents reported for the CSW landfills all over the world. The CSW landfill is different from natural soil slope in many aspects. Firstly, the materials of the CSW landfill were normally less-consolidated and hence with low shear strength given that the soil properties largely affect the strength behaviour (Council of the European Union 1999). Secondly, the CSW landfill was typically under the effects of combined loading and environmental factors, such as rapid loading arising from the increased amount of CSW stacking and heavy rainfall. Finally, the CSW landfill could undergo large deformations over a long period (i.e., greater than 1 mm) for which the effective monitoring methods lack. The CSW landfills face high risk of collapse due to all these characteristics. Significant contributions have been made on hazard identification and mitigation strategies for the CSW landfills (Blight 2008; Zou 2016; Yang et al. 2017). However, as pointed out by many researchers, the CSW landfill composes of complex soil-rock mixture with highly nonlinear geotechnical properties and is in operation under complicated geological conditions, it follows that the field monitoring could be the most effective means for the risk prediction and evaluations (Xu et al. 2019a; Zhou et al. 2018). Although the instability of the CSW landfills is known to be the consequence of excessive and irregular deformation, the measurement for such a high level of deformation (i.e., greater than 1000 mm) is indeed a great challenge in engineering practices, especially when the measuring transducers are required to have high strength and durability, corrosion resistance as well as availability in mass production. Many types of displacement transducers are presently accessible such as inductive, magnetic, capacitive, ultrasonic and optical transducers, while various conventional sensors such as linear variable differential transformer (LVDT) and vibrating-wire strain gauges (VWSG) are still prevailing for health monitoring of geotechnical structures. However, all of these conventional sensors have some limitations, such as limited measurement range, low resolution, poor durability to long-term adverse environment and high failure rate (Pei et al. 2020; Hong et al. 2019; Zhang et al. 2018).
In recent decades, the fibre optic sensing technology has shown great potential in structure monitoring and disaster prevention. In comparison to the traditional sensors, the fibre Bragg grating (FBG) sensors offer massive advantages, such as light weight, immune to electromagnetic interference (EMI), convenience of installation, long-term stability (Xu et al. 2018a; Xu et al. 2018b). The accurate and reliable monitoring results from FBG sensors have attracted increasing interests from geotechnical engineering community, making FBG a promising means to monitor the behaviour of geotechnical structures. Various optical fibre sensors have been proposed for displacement measurement. Hill et al. (1978) firstly fabricated a Fibre Bragg Grating (FBG). Since then, many new methods were developed to measure soil deformations, such as the sensing bar, bent mode fibre, and plastic optical fibre sensors used for curvature and strain measurements in a structure subjected to flexural and tensile loads (Yang et al. 2019; Zhang et al. 2019).

The rapid development of fibre optic technology has facilitated its applications in many engineering fields. In terms of municipal solid waste landfill monitoring, the use of the fibre optic sensing method has covered many environmental and hydrological aspects, such as pollutants monitoring in landfill leachate (Silva et al. 2009), trace gas detection across landfill site (Stewart et al. 2003), the deformation measurement and moisture intrusion detection for barrier facilities (e.g., landfill lining system and cap) (Zamara et al. 2012; Weiss 2003). Recently, Tao et al. (2018) investigated the feasibility of Brillouin-based distributed optical fibre sensors in the stability assessment of open-pit mine dump using laboratory physical model tests and numerical simulations. Despite these studies, very limited works has been reported on the application of fibre optic in monitoring the deformation of full-scale CSW landfill slope (Zhang et al. 2014). The commonly employed approaches to measure the deformation of CSW landfill/dump slope involve the total station theodolite, GPS and remote sensing methods such as LIDAR technology. However, these methods can only offer data on the surface deformation; given that the waste dumping is a dynamic working process and the surface displacement keeps changing, the above surface monitoring means may lead to frequent and unreliable warning of landfill failure. Therefore, it is clear that the fibre optic technology, which is capable of providing three-dimensional large deformation measurements both in the surface and at depth, has distinct advantage over traditional methods in the CSW landfill monitoring.

In this study, a CSW landfill landslide that occurred in Shenzhen, China was reviewed and lessons learned from this case showed that the internal deformations of landfills would be a significant factor for the stability evaluation. Thus, a new FBG sensing approach was proposed for measuring large internal deformation of landfills. The working principles, designs, package and calibrations of the fibre-optic based large deformation transducer (FDT) are elaborated. Finally, an early warning system with risk assessment and stability analysis of CSW landfills was proposed and discussed. The potential and suitability of this technique in monitoring CSW landfills was interpreted in terms of its ability of capturing extra-large internal deformation of landfills.
2. Lessons learned from the Shenzhen CSW landfill failure

2.1. Landslide of the Shenzhen CSW landfill

On December 2, 2015 a landslide of CSW landfill occurred in Shenzhen city, China, causing 73 deaths, 4 missing persons and 17 injuries with a total economic loss of 881 million (Yin et al. 2016; Yang et al. 2017; Zhan et al. 2018). This CSW landfill site was originally an abandoned quarry with large pits filled by water of about 90,000 m³, as shown in Figure 1. The placement of CSW was initially designed to be implemented in the form of 10 Terraces (designated as T0 to T9). Before sliding, Terraces T0 to T6 have been completed and afforested while Terraces T7 to T9 are still being filled (Yin et al. 2016). The total volume of CSW in landfill is about 5.83 million cubic metres, which is mainly composed of engineering waste soils mixed with a small amount (0.73 million cubic metres) of concrete bricks and domestic refuse (Zhan et al. 2018).

Figure 1. Remote-sensing photos of 4 stages before and after the Shenzhen CSW landslide: (a) the quarry site before the CSW landslide; (b) start of the CSW landfill; (c) two months before sliding of the landslide; (d) accumulation profile of the landslide (photos from Google Earth).
As shown in Figure 2, this landslide is among the largest CSW landfill landslides in the world as its volume reaches more than 2.7 million cubic metres. The sliding distance is as far as 1.1 kilometres. The elevation of Terraces T0 is 56.9 m and the highest elevation of the formed landfill slope is 150.0, indicating that an actual height of the landfill is 103.1 m. Around 6:00 on December 2, 2015 cracks with the width of 40 cm and the length of tens of metres were found on the working platforms at the top of the CSW landfill. At 11:28, the landslide initiated and the toe of sliding surface was located at the underlying bedrock between Terrace T3 and T4 in the north of pit. After exiting off the initial failure surface, the major slide mass continuously moved forward over 700 metres, being flow-like and fan-shaped before coming to rest. The soil mass movement completely ceased at a distance of 1100 m from the trailing edge of the landslide (Yin et al. 2016; Zhan et al. 2018).

There are three major reasons accounting for this landslide at Shenzhen CSW landfill:

1. There was no effective drainage system. A detailed site investigation was carried out by Zhan et al. (2018) after this CSW landfill landslide. Figure 3 presents particle size distribution curves of CSW materials and rainfall data for this landfill site. Figure 3 indicates that samples collected from the lower part of the landfill slope have higher content of fine grain compared with samples taken at the top layer. Due to the lack of effective drainage system, heavy rainfall induces a quick increase in the water content of upper materials which have a relatively high permeability coefficient and allow the water to flow downward to the lower layer. However, the waste materials at the lower part of the landfill have a lower permeability due to relatively higher fine particle content. Thus, the accumulated water within lower layer cannot be fully and quickly discharged, resulting in very high excess pore pressure and a significant decrease in the effective strength of underlying materials. On the other hand, the rainfall could yield an abrupt
increase in the downward thrust force due to the increase in soil unit weight, and this was combined with the reduction in the effective shearing strength of underlying materials to cause the potential sliding zone at the bottom.

2. The second direct reason is the fast loading and the overfilling of waste beyond the capacity. Figure 1 illustrates four major stages of the CSW landfill before and after the landslide, indicating that the CSW landfill was loaded in a very short time. In addition, the drainage system was not properly designed, which induces gradual increase in downward thrust and hence leads to instability of the landfill slope and final overall

Figure 3. (a) variation of soil grading with depth; (b) statistic data of rainfall (after Zhan et al. 2018).
sliding. The large volumes of slide mass with high potential energy generate a huge impact to the surrounding facilities. The original design capacity for this landfill was 4 million cubic metres, however, the actual volume of CSW at landfill was 5.83 million square metres, which is 1.83 million square metres more than the limits. At the same time, the speed of CSW placement is rather fast, and many of the landfill material are relatively loose without being sufficiently compacted.

3. The third major cause was the lack of effective measurement method as well as inappropriate measures to handle dangerous situation before the incident. The lack of vigilance and irresponsible management of the landfill in emergency response directly led to heavy casualties and property losses.

2.2. Key factors related to the hazard identification and mitigation strategies

In this case study, two key factors related to the landslide hazard can be summarized into two following categories:

1. The lack of effective risk identification and evaluation approaches: as mentioned in the foregoing, no effective field instrumentation was installed on this CSW landfill. The apparent cracks had been observed by on-site workers, and they first observed the cracks on the top working platform of the CSW landfill at 6:00, which is more than 5 hours earlier than the initiation of landslide. Around 11:20, it was found that the bulge occurred at Terrace T4 of the landfill, and the bulge continued to move and 8 minutes later, the large-scale landslide occurred and lasted for 13 minutes, damaging and burying 33 buildings. From this case study, we can find that a measurement system with slope stability evaluation and alarm system is essential for the hazard identification and mitigation strategies.

2. The lack of effective field large-deformation measurement approaches and early-warning system: the discrete and loose waste materials at landfill have relatively low shearing resistance. This combined with the overloading leads to the occurrence of large displacement within the landfill slope. Such a high level of deformation proceeds and becomes more significant when the slope is subjected to severe environmental condition such as heavy rainfall. The large deformation has been indicated by the long and wide cracks on the top of working platform of the landfill and the bulging deformation or cracking at the position between the Terrace T3 and T4, where the toe of landslide is located. Therefore, it can be envisaged that an effective method for monitoring large deformation of the landfill slope could have capacity to provide sufficient and accurate information used for early warning. From this perspective, a new sensing method for large deformation is introduced to solve this issue.

3. Development of a new FBG sensing technology for the extra-large internal deformation of the landfills

3.1. Working principle of the FBG

Since Hill et al. (1978) fabricated the first FBG in an optical fibre with a laser beam, the FBG sensing technology has been widely applied in civil engineering due to its inherit
merits as compared with traditional electrical sensors, such as light weight, free of electromagnetic interference and corrosion. It can also form a quasi-distributed measurement network by spatially multiplexing several FBGs along the same optical fibre line.

A periodic grating was written in the core of the fibre by ultraviolet light to enable periodic variation in the refractive index of the fibre core. Figure 4 shows the working principle of the FBG sensors. When there is a board light injecting to the optical fibre, the special light would be reflected with the presence of a FBG sensor, and the rest signal would be transmitted to the next sensor. The reflected signal would be concentrated to a special wavelength which has a linear relationship with the strain and temperature. The relationship between the shift of the reflected wavelength and the surrounding strain and temperature can be expressed as follows:

\[
\frac{\Delta \lambda_B}{\lambda_B} = c_1 \varepsilon + c_2 \Delta T
\]  

where \( \lambda_B \) is the initial Bragg’s wavelength under the strain-free condition, \( \Delta \lambda_B \) is a shift in the Bragg’s wavelength due to the external strain \( \varepsilon \) and temperature variation \( \Delta T \). For germanium-doped silica fibre, \( c_1 = 0.78 \times 10^{-6} \), and \( c_2 = 6.67 \times 10^{-6}/^\circ C \). All these parameters are unchanging for a specified fibre. It can be concluded from Eq. (1) that the external strain is measured, provided the shift of Bragg’s wavelength \( \Delta \lambda_B \) is detected and the temperature variation \( \Delta T \) is compensated. In this study, FBGs are fabricated with a phase mask method and have a gauge length of 10 mm, with wavelength ranging from 1510 nm to 1590 nm, a 3-dB bandwidth of 0.5 nm, and a reflectivity of 20 dB.

3.2. A New approach for the large internal deformation measurement

As shown in Figure 5, a novel fibre-optic based large deformation transducer (FDT) based on fibre-optic principle was proposed to measure internal deformation in soil.
mass. The FDT consists of a spring, stainless steel rod, connection steel rod, a protection tube and two FBG sensors. The two FBG sensors were embedded in the connection steel. The FBG sensor was glued and protected in a package unit. The length of packing unit can be determined by the measurement range, and a typical length of the packing unit is 800 mm. The connection rod would be connected with a flat plate which would deform with the soil mass and structural load simultaneously. The FDT was vertically installed inside the soil mass. The bottom of the FDT was mounted in a hard stratum. The top of the FDT was deformed with the soil, and the deformation of soil will result in the deformation of the flat plate, which will further compress the steel rod. With the compression conducted by the steel rod, the FBG sensors have extension strains. The strains of the FBG sensors will be detected by the wavelength shifts of the reflected lights when a broadband source of light is injected into the fibre.

Supposing that the steel plate of the FDT transducer has a deformation $\Delta d$ as shown in Figure 5, this deformation will induce the variation in the force of the spring $\Delta F$ and the strain change of the FBG sensors. Thus, the changed force of the spring $\Delta F$ is:

$$\Delta F = k \cdot \Delta d = E_m \cdot \Delta \varepsilon_{FBG} \cdot A_m$$

where $\Delta F$ is spring force under the extension of $\Delta d$, $k$ is the elastic coefficient of the spring; $E_m$ is the elastic modulus of the host material for the FBG sensors, which is assumed as a linear elastic material; $\Delta \varepsilon_{FBG}$ is the strain of the host material, which is
the average strains of the FBG_A and FBG_B; $A_m$ is the sum of the section area of the host steel rods. Therefore, the relationship can be rearranged as:

$$\Delta d = \frac{E_m}{k} \cdot \Delta \varepsilon_{FBG} \cdot A_m$$  \hspace{1cm} (3)$$

The deformation $\Delta d$ can be determined, provided the extension strain of the rod $\Delta \varepsilon_{FBG}$ is measured.

As shown in Figure 5, the extension strain can be measured by the two FBGs, referred to as FBG_A and FBG_B. When the system is monitoring deformation, the strains induced by the axial tension and temperature are the same for these two FBGs. The strains in these two FBGs may differ from each other, but this difference must be under a small value. Therefore, the extension strain $\Delta \varepsilon_{FBG}$ of the host material rods, where the FBGs are installed, can be expressed as follows:

$$\Delta \varepsilon_{FBG} = \frac{1}{2} (\Delta \varepsilon_{FBG_A} + \Delta \varepsilon_{FBG_B})$$ \hspace{1cm} (4)$$

where $\Delta \varepsilon_{FBG_A}$ and $\Delta \varepsilon_{FBG_B}$ are the measured strains of FBG_A and FBG_B. According to Eq. (3), the deformation of the soil surface can be obtained as:

$$\Delta d = C \Delta \varepsilon_{FBG}$$ \hspace{1cm} (5)$$

where $C = \frac{E_m A_m}{k}$ is the coefficient between deformation and extension strain measured by the FBG sensors. A positive or negative $\Delta d$ represents the uplift or deformation of the soil surface level relative to initial state.

### 3.3. Fabrication approach

The measurement range and resolution of FDT relate to several parameters, such as the dimension, Young’s modulus of the host material rod, the elastic coefficient of the spring, and the strain range and resolution of the FBG sensors. In order to design a relatively high-resolution FDT with a relatively large measurement range, these parameters are studied in this section.

According to Eq. (2), the measurement range of the transducer is the minimum between the maximum displacement of the spring and the maximum permitted displacement of the stainless steel rod. For the increase of the measurement range, the length of the steel rod and the column package unit should be increased and the maximum extension strain should be within the measurement range of FBGs.

For column host material:

$$A_m = \frac{1}{2} \pi D^2$$ \hspace{1cm} (6)$$

For square host material:

$$A_m = 2Bt$$ \hspace{1cm} (7)$$

where $D$ is the diameter of the host material column, $B$ is the width of the section of square host material; $t$ is the thickness of the section above. It is supposed that the FBGs
have a resolution $R_{FBG}$. The resolution of the transducer $R_t$ is defined as the deformation of the plate under the strain equal to $R_{FBG}$, and is given according to Eq. (5) as follows:

$$R_t = C \cdot R_{FBG}$$  \hspace{1cm} (8)

A lower resolution denotes a better accuracy of the transducer. In order to determine the dimension and Young’s modulus of the host material rod, a parametric study is carried out and the results are shown in Figure 6 and Figure 7. It can be found that the transducer’s resolution decreases as the diameter, Young’s modulus increase respectively, and resolution increases as the elastic coefficient of the spring increases.

Figure 6. Resolution of the designed transducer as functions of the diameter and (a) Young’s modulus, (b) elastic coefficient of spring.
The FDT can be designed with adjusted measurement range. Figure 8 shows a typical FDT which can measure the deformation of up to 1200 mm. By selecting different elastic coefficients for the spring and the material of package unit, the FBG displacement transducer can be designed and developed. This device can be customized according to different requirements of measurement range and resolution by changing the elastic coefficient of the spring.

3.4. Calibration

A step deformation was applied on the end of the FDT and the wavelengths of the FBG sensors were taken by the FBG sensing interrogator. Both loading and unloading tests were conducted to verify the performance of the FDT. A typical calibration test consists of 120 steps in which the FDT was compressed from step 1 to step 60 and extended...
from step 61 to step 120. A laser displacement sensor was used to measure the changed deformations of the FDT during each step. Figure 9(a) and (b) show the measured wavelength of the FBGs varying with steps and applied displacement, respectively.

3.5. Field installation

Upon the fabrication of \( n \) FDTs, they are connected together nose to tail and in the second model shown in Figure 10(a). In order to install in the CSW landfill, a corrugated tube is used to form a deformation monitoring system shown in Figure 10(b). The corrugated tube is used to conduct deformation strain to FDTs, and the rigid stainless steel rod connected all transducers to ensure that all the FDTs are in the same vertical line. The FBGs are chosen to have different wavelengths and thus can be connected together through a single optical fibre. It is assumed that the \( i \)-th transducer (\( i = 1, 2, \ldots, n \)) has an deformation \( \Delta z_i \), as shown in Figure 10(a). Meanwhile, the comparative depth of transducer \( h_i \) is measured when the system is being installed.

It is assumed that the comparative displacement of the No. (i-1) transducer to No. \( i \) transducer are \( \Delta z_1, \Delta z_2, \Delta z_3 \ldots \Delta z_n \) (\( i = 1, \ldots, n \)) and the comparative soil thickness are \( h_1, h_2, h_3 \ldots h_n \) above the comparative level of the next transducer. As all transducers and the other parts were connected together through a main steel rod or a corrugated tube and the transducers are monitoring the displacement of the soil, the deformation of the soil can be given by:

\[
\Delta z_i = \text{measured wavelength of the FBGs} - \text{initial wavelength of the FBGs}
\]

\[
h_i = \text{measured depth of transducer} - \text{initial depth of transducer}
\]

\[
G = \frac{\Delta z}{h_i}
\]
\[ S = \sum \Delta z_i = \Delta z_1 + \Delta z_2 + \ldots + \Delta z_n \]  

where \( S \) is the comparative deformation, which takes the base line as a datum line. The total height of the measurement can be given:

\[ H = \sum h_i = h_1 + h_2 + \ldots + h_n \]  

where \( H \) is the thickness of the measured soil. It can be found in Eq. (10) that the deformation of a measured point is the value of the soil level variation of the corresponding FDT. In other words, the deformation of all interested points can be measured by the deformation monitoring system.
Three prototypes of small-scale FDTs were fabricated in the laboratory, whose dimensions are the same as the prototype FDT given in Section 3.3. These three FDTs have different FBG wavelengths, each with a total length of 100 mm. The FDTs have different wavelengths so that these FDTs can be connected in series with single-mode optical fibres. The wavelengths will be changed with the deformations and the wavelength information was then interpreted by a Micron Optics SM130 interrogator. Before the formation of a monitoring system as indicated in Figure 10, each FDT should be calibrated. A number of FDTs were connected in series through the steel rod. Simultaneously, the FBG sensors were connected in one optical fibre through the FC/APC couples.

4. Csw landslide risk assessment

4.1. Stability analysis

The stability of the CSW landslide was related to many factors, such as the dumping process of the CSW, supporting structures of the landfill, rainfall infiltration, ground water fluctuation, and shear strength of soil. Risk assessment was conducted by the
establishment of the numerical model together with the field monitoring data. In the numerical model, the soil parameters were treated as random variables. With the Bayesian framework, the prior distribution of soil parameters and the errors between the calculated results and the measured values can be updated. The joint posterior distribution of the error calculated by the numerical model can be expressed as:

\[ P(\varepsilon, \theta_1, \theta_2, ..., \theta_n | y) = \int P(\varepsilon | \mu_\varepsilon, \sigma_\varepsilon, \theta_1, \theta_2, ..., \theta_n) P(\mu_\varepsilon, \sigma_\varepsilon, \theta_1, \theta_2, ..., \theta_n | y) d\mu_\varepsilon d\sigma_\varepsilon \] (11)

where \( P(\varepsilon | \mu_\varepsilon, \sigma_\varepsilon, \theta_1, \theta_2, ..., \theta_n) \) is the probability density function of numerical model calculation error; \( P(\mu_\varepsilon, \sigma_\varepsilon, \theta_1, \theta_2, ..., \theta_n | y) \) is the posterior probability density function of \( \mu_\varepsilon, \sigma_\varepsilon \) and the elastic modulus; \( \mu_\varepsilon \) and \( \sigma_\varepsilon \) are the mean and standard deviation of the calculated errors of the numerical model. The probability density function of error calculated by the model can be expressed as (Zhang et al. 2010):

\[ P(\varepsilon | \mu_\varepsilon, \sigma_\varepsilon, \theta_1, \theta_2, ..., \theta_n, y) = \frac{1}{\sqrt{2\pi\sigma_\varepsilon}} \times \exp \left[ -\frac{(\varepsilon - \mu_\varepsilon)^2}{2\sigma_\varepsilon^2} \right] \] (12)

The posterior probability density function of \( \mu_\varepsilon, \sigma_\varepsilon \) and the elastic modulus by using the Bayesian theorem can be expressed as:

\[ P(\mu_\varepsilon, \sigma_\varepsilon, \theta_1, \theta_2, ..., \theta_n | y) = k P(y | \mu_\varepsilon, \sigma_\varepsilon, \theta_1, \theta_2, ..., \theta_n) P(\mu_\varepsilon, \sigma_\varepsilon, \theta_1, \theta_2, ..., \theta_n) \] (13)

where \( k \) is a normalized constant; \( P(y | \mu_\varepsilon, \sigma_\varepsilon, \theta_1, \theta_2, ..., \theta_n) \) is the likelihood function reflecting the numerical model calculation fit with the field data; \( P(\mu_\varepsilon, \sigma_\varepsilon, \theta_1, \theta_2, ..., \theta_n) \) is the prior distribution of \( \mu_\varepsilon, \sigma_\varepsilon \) and the elastic modulus. The likelihood function is the probability density function of the numerical model errors under the condition of given random variable. In this study, considering the influence of the uncertain parameters on the predictions, the relationship between the uncertain parameters and the measured deformations (i.e., \( y \)) were established by numerical model. The likelihood function was established for the numerical model error (Wang et al. 2016), which can be expressed as:

\[ P(y | \mu_\varepsilon, \sigma_\varepsilon, \theta_1, \theta_2, ..., \theta_n) = \frac{1}{\sqrt{2\pi\sigma_\varepsilon}} \times \exp \left[ -\frac{(y - g(\theta_1, \theta_2, ..., \theta_n) - \mu_\varepsilon)^2}{2\sigma_\varepsilon^2} \right] \] (14)

The stability of the CSW landfill with supporting structures could be expressed by the factor of safety (\( FS \)) using the following expression:

\[ FS = \frac{c_u N_{c1}}{D(\gamma_s - c_u/B')} \] (15)

where \( \gamma_s \) and \( c_u \) are the average total unit weight and undrained shear strength of soil, \( N_{c1} \) is equal to 5.7 corresponding to the bearing capacity of a long rough footing; \( B' \) is the width of failure surface which is limited to \( B/\sqrt{2} \) or \( T \) whichever is smaller; \( T \) is the thickness of clay below based of the CSW landfill.
4.2. Risk assessment

The landslide risk assessment of the CSW landfill was carried out by the combination of field fibre optic sensing technology with deformation measurement and the numerical model for the stability analysis. As mentioned above, the risk assessment with the numerical model would result in large errors in the initial monitoring stages due to the uncertainty of parameters of the CSW landfills. Thus, the updating method was used for the back-analysis of CSW parameters. Figure 11 shows the framework of risk assessment with the updating method. Firstly, the site information and field monitoring data were collected. Secondly, the numerical model with the detailed information of the field conditions was established. The mean and coefficient of variation of input parameters (e.g., cohesion $c$ and friction angle $\phi$) were determined with laboratory test results. Thirdly, the autocorrelation matrix and random field $G(x, y)$ of the CSW material parameters were established. The random field of soil parameters was treated as the input parameters, and the field FDT results were taken as output data. With the prior knowledge and likelihood function, the posterior distribution was derived. Thus, the CSW landfill response in the next stages would be predicted with the model.

Figure 12 shows the diagram of the risk alarm system for the CSW landfills. The risk assessment was carried out based on the real-time field responses from the FDT sensors and stability analysis with the numerical model, which was calibrated through model updating. The chip processor is used as a processing module, which is combined with the monitoring data at various locations by wireless means. The early warning system can be divided into two parts: an on-site early warning system and cloud platform early warning information that can send messages to the concerned people. Different colours of LED lights correspond to different degrees of landfill deformation. The threshold values for different alarm levels could be adjusted according to various specific projects. The warning levels can be represented by the colours of the LED lights, such as the green, blue, yellow, and red colour. The evacuation instruction starts to light up once the landfill deformation reaches a certain danger level. The proposed alarm system could provide real-time safety status of the CSW landfills through its own integrated warning light (different colours reflect different degrees of risks), which could benefit for the hazard identification and mitigation.
strategies of the construction solid waste landfill. It is of note that threshold values for alarm messages are dependent of landfill type and normally based on an expert interpretation of the stability conditions. An example of alert levels and planned solutions are provided in Table 1; the threshold values listed in the Table 1 may need to be adjusted according to the real situation of the investigated CSW landfill.

4.3. Discussions

The fibre sensors have many advantages including the resistance to the electromagnetic and radio frequency interference (RFI), light weight, compact size, multiplexing capabilities, resistance to the corrosion and high accuracy and stability. As the fibre sensors directly transferred the strain or temperature to the optical wavelength which is not affected by the optical energy and fibre losses, the long-term stability and measurement accuracy can be ensured. Despite the above merits, the disadvantages of this fibre optic monitoring system for the field monitoring should be taken into considerations. The two major limitations of fibre optic sensors are the fragile and cost. Firstly, the fibre sensors are susceptible to be damaged during field installations. Thus, a robust protection approach should be adopted. Secondly, the cost of fibre optical interrogator is still relatively high (e.g., ~US $30,000 for static FBG interrogator and ~US $40,000 for dynamic FBG interrogator). However, the interrogator can be used for large number of sensors due to the multiplexing capabilities of fibre sensors. In addition, the interrogator can be reused in many different projects. Therefore, by considering large amount of sensors and long-term monitoring, the cost of optical fibre sensors are quite competitive with conventional vibration wire strain gauges.
5. Conclusions

A case study of Shenzhen CSW landfill landslide indicated that the construction solid wastes have great variety in composition and grading and geotechnical properties. The landfill materials are normally under less-consolidated state due to very rapid loading arising from fast dumping of the CSW. Under the combined effects of heavy rainfall and overfill, the discrete and loose landfill materials generally exhibit very large internal deformation which is difficult to be monitored using conventional transducers. The lack of effective monitoring and early warning system would result in difficulty in the risk assessment of the industrial solid waste landfill. This study focussed on the hazard identification and mitigation strategies for the construction solid waste landfill. Major conclusions are summarized as follows:

1. A case study of landslide of CSW landfill was conducted. Lessons learned from the failure of risk assessment and preventions show that the effective, on-site, internal large deformation measurement and efficient risk assessment with early warning system are significant for the risk identification and mitigation.
2. A new fibre-optic based large deformation transducer (FDT) was proposed and the design principle, package and laboratory calibration as well as working principle for hazard identification were elaborated. This new method could measure the deformation inside the CSW of up to 1200 mm, and thus it could provide effective tool for risk assessment of the CSW landfills.
3. The stability analysis method and application framework associated with the use of this technique to assess landslide risk of landfill were proposed. This new approach possesses the advantages of capturing excessive and irregular deformation of the CSW dump. The stability analysis approach along with the early warning system could provide an effective and efficient tool for the hazard identification and mitigation strategies for the CSW landfills.

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Table 1. Example of alarm levels and planned solutions for CSW landfill failure.

| Velocity (mm/day) | Alarm level and judgment | Planned response |
|-------------------|--------------------------|------------------|
| 0.1-0.5           | Level 1 - Green; normal situation | Regular inspection and maintenance. |
| 0.5-1.5           | Level 2 - Blue; awareness. The fluctuations of the displacement velocity are observed in some fibre-optic sensors | Frequently review of monitoring data and compare the deformation data at various locations. |
| 1.5-4             | Level 3 - Yellow; high attention. Increased displacement velocity are found in several fibre-optic sensors | Intensive field survey and inform relevant departments for the emergency preparation |
| 4-8               | Level 4 – Orange; high hazard. Continuous acceleration in the displacement velocity indicated by multiple fibre-optic sensors. | Alter government to prepare for evacuation |
| >8                | Level 5 – Red; landslide failure. Further acceleration of velocity | Evacuation |
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Data availability statement

The data that support the findings of this study are available from the corresponding author, Qingbing Liu, upon reasonable request.

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