The Development of a Diagnostic Model for the Deterioration of External Wall Tiles of Aged Buildings in Taiwan

Li-Wei Chiang*, Sy-Jye Guo, Chih-Yuan Chang and Tzu-Ping Lo

1 Ph.D. Candidate, Department of Civil Engineering, National Taiwan University, Taiwan
2 Professor, Department of Civil Engineering, National Taiwan University, Taiwan
3 Associate Professor, Department of Civil Engineering, Feng Chia University, Taiwan
4 Assistant Professor, Department of Environment and Property Management, Jinwen University of Science and Technology, Taiwan

Abstract
This study creates a deterioration diagnostic model for the external wall tiles of aged buildings, using both stage 1 and stage 2 diagnostic methods. The visual test results are categorized based on their impact on public safety, and renovation strategies are proposed. The stage 1 diagnosis mainly adopts the D.E.R. visual inspection the deterioration assessment method. After producing an external wall tile Condition Indicator (CI) for the stage 1 diagnostic results that fall in a gray area, this research performed a stage 2 diagnosis using a tap tone test, followed by a fast Fourier transform and pattern recognition to analyze the tapping results. Finally, this study provides deterioration evaluation criteria for external wall tile replacement recommendations and a standard operating procedure for the deterioration diagnosis. This study also suggest directions for the future amendment of regulations and provide a basis of references for the government in determining urban renewal, renovation and maintenance strategies.

Keywords: external wall tiles; public safety; visual diagnosis; tap tone diagnosis

1. Introduction
In recent years, Taiwan has experienced frequent safety incidents involving the external walls of buildings. The most common incidents include falling tiles, falling advertising signage and falling exposed pipelines, all seriously impacting the surrounding environment and public safety. On March 14, 2015, a tile falling incident in Taipei City, Taiwan, resulted in a fatality. According to the Taipei City Government Statistics, there were 1188 buildings listed for control as important cases with spalling wall tiles. The government of Kaohsiung City, Taiwan investigated the 6492 apartment buildings with six or more floors in the city. There were 859 buildings with tiles spalling. Kaohsiung City government listed 367 buildings as important cases for control. According to research data (Chang, 2008), construction in Taiwan peaked in the years 1981 and 1994. According to this research, Taiwanese buildings experience significant deterioration after 30 years. Safety check requirements for Taiwanese buildings should thus peak in 2011 and 2024. Integrating news relating to fatalities in tile-falling incidents in Taiwan, this research see an immediate need for a complete diagnostic mechanism and preventive method for the further occurrences of such public safety incidents.

To effectively drive external wall replacement safety checks and studies on evaluation systems, the industry requires relevant empirical results and evaluation criteria. This study aims to employ data collection and empirical research to provide a basis of reference and an evaluation method for use in external wall tile diagnosis.

2. External Wall Health Check Mechanisms, Technology and Causes of Tile Deterioration
2.1 Rules and Regulations for Building Safety Checks
Unlike other developed countries, Taiwan does not have regulations in place for "external walls of buildings" (Guo and Li, 2012). Looking at other countries' inspection systems, the author find the Hong Kong Buildings Department promoting a "Mandatory Building Inspection Scheme," which began in 2005. In 2011, Hong Kong imposed regulations on houses and multipurpose buildings that are more than 30 years old. Inspection items include external walls and other physical components, structural components,
drainage systems and fire safety components. The inspection frequency for buildings 30 years of age and older is once a decade. The Japan Building Disaster Prevention Association and the Japan Building Disaster Prevention Association of the Ministry of Land, Infrastructure, together with various professional Japanese architectural bodies, have promoted new measures based on the concept that buildings are like people and require health check-ups. (Huang, et al., 2010) (Taketo, 2000)

2.2 Analysis of Building Health Checks and Maintenance Technology

The main discussion items of this empirical study on the health of buildings include inspection items, the frequency of inspection, the setting of inspection standards, deterioration evaluation, technology and the planning of management systems. Taketo (2000) proposed non-destructive testing that uses radiographic, ultrasonic, infrared, spontaneous and potential techniques. Diagnosis requires highly specialized personnel, simple tools, precision equipment and instruments. Also, these technologies have to be applied with a degree of professional knowledge comparable to that of the field of pathology in the medical sciences (Chang, 2008). Research (Chiang, 2014) shows that different deterioration inspection items have different focuses (Table 1.). Tong (2006) studying irregular tile surfaces, used a tap tone method and artificial neural networks to develop a health check method for the tile-wall bonding integrity of old buildings.

Table 1. Visual Investigation Emphasis

| Investigation Item | Emphasis for Investigation |
|--------------------|---------------------------|
| peeling, float, bump | When a piece of tile is peeling, the chance for surrounding tiles to peel off is also high, sometimes resulting in a large area of float and bump. The most important significance of a visual investigation is to understand the situation. |
| fouling | To determine whether a tile's surface is fouling or a result of water infiltration behind the tile. |
| dampness | Water penetrating of tiles leads to a float problem. |
| efflorescence | If water enters the voids behind tiles or concrete float has likely occurred. |
| cracking | When the building surface is cracking, the tiles are prone to generating peeling or float. |

For the external wall diagnosis and research of maintenance technology for Taiwan's buildings, Yang and Nian (2012) proposed an evaluation method for the at-concern external walls of buildings. Chiang (2014) suggested building a visual diagnosis evaluation model for the external walls of buildings, similar to the D.E.R. (Degree, Extent, Relevancy) visual diagnostic method used for bridges. Through empirical research, the study proposed diagnostic evaluation, grades of deterioration and repair standards as methods to determine the degree of damage and to propose recommendations, reducing the risk of external wall tile safety incidents. Eldash (2011) used the visual inspection of a building to record any clear deterioration in the structure or the serviceability of the building. Chang (2008) considers this necessary aesthetic maintenance work.

2.3 Analysis of the Causes of External Wall Tile Deterioration

External wall tiles are directly attached to a building's external walls. With years of direct exposure to wind, rain, sunshine and dew, as well as due to climatic factors (humidity, temperature differences and daily sunlight), construction quality and maintenance management, conditions such as peeling (falling), bulging and detachment can develop as a form of normal "wear and tear". In Chew M.Y.L.'s study (1999), temperature was shown to have a significant effect on the bonding strength of adhesives during the strengthening process. The study observes that after the cement stucco layer is applied, followed by a layer of mastic, the length of "open time" is important. If the mastic dries too quickly, the setting time will be reduced, causing difficulties in tile adhesion to the external wall.

If the tiles bulge (Fig.1.), the problem lies in the adhesion between the mastic and the tiles. After summarizing the causes of external wall tile deterioration, this study discovered four main factors:

Fig.1. Common Tile Bulging Scenarios in Taiwan

Fig.2. External Wall Tiles Deterioration Factors
human factors, construction methods, tile materials and "other". Fig.2. shows the causes of tile deterioration as posited by this study.

3. Methodology
3.1 Visual Diagnostic Evaluation Method
This study adopts visual inspection as the author preliminary diagnostic method for the external wall tiles of buildings. The research three reasons for using this method follow.
1. It is an economical, simple and fast inspection method to effectively determine the safety of a building's external wall tiles.
2. A visual diagnosis can be performed periodically, and quantitative data can be used for continuous maintenance tracking, allowing for decisions on repair priorities.
3. A visual diagnostic evaluation is a preliminary diagnosis performed only on a deteriorating object, thereby simplifying the diagnostic process and evaluation chart.

This study primarily focused on developing a testing method for the commonly used types of tiles (Rectangular Tile, one of the common tile in Taiwan) on the exterior walls of Taiwan's buildings. The methodology adopts the D.E.R. & U. evaluation method used in the "Taiwan Bridge Management System" (Tseng et al., 2001). Regular visual inspection of all the bridges in Taiwan is carried out in accordance with this method. Further, it has been verified as reliable for more than 20 years. However, there are a total of 28 members on the bridge that need to be visually inspected. Inspection of the tiles of the external walls is a single project.

Therefore, the "U" part (maintenance urgency) in the original D.E.R&U visual assessment method was excluded in this study. Chiang (2014) and Guo (2011) follows with the spirit and logic of this approach, and revised to use three D.E.R assessment benchmarks for visual inspection. This study proposes a modification of the visual diagnostic evaluation chart for external wall tiles. Table 2. shows this research amended version of the chart (with the addition of remarks).

In general, an external wall structure can be split into a structural protective layer, stucco layer, adhesive layer and tile layer. This study posits that when tiles begin to discolor, peeling may occur. The author call this "level 1 deterioration". Following the structural order, the other three levels can be categorized as "tiles falling"; "paint layer visible" (bulging can be considered to be a peeling off from the stucco layer); "stucco layer peeled"; "protection layer visible"; and "structural protection layer damaged." Based on differing degrees of damage to an external wall's structure, the deterioration condition is determined (Table 3.).

In terms of the extent of deterioration, this study relies on the ratio (as a percentage) of the deterioration area to the total surface area of the external wall for

Table 2. Visual Diagnosis Evaluation Criteria for Building External Wall Tiles

| 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| D | Normal | Expansion, discoloration, efflorescence | Tiles falling, paint layer visible | Stucco layer peeled, protection layer visible | Protective layer damaged |
| E | 0% | No effect | A few specific users | Many specific users | A few unspecified users |
| R | Road width < 1m | 1 to 2 m road width | 1 to 3 floors | 2 to 6 m road width | 6 to 12 m road width |
|   | 0 to 1 floor | 1 to 3 floors | 4 to 6 floors | 7 to 9 floors | 10 floors or more |

Note 1: Inspectors should pay attention to a building's external corners (such as exposed structures), openings, parapets, balconies, and locations of attachments to walls (such as signage or rain awning), as these are the places at which tiles are prone to damage.

Note 2: Inspectors should determine the R value and carefully observe if the circulation is near the arcade or if the building has setbacks; the inspector should also.

Table 3. Deterioration Degree

| Level 0(Normal) | Level 1(Expand, discoloration, efflorescence) | Tiles falling, paint layer visible |
|----------------|------------------------------------|----------------------------------|
| Level 3(Stucco layer peeled, protection layer visible) | Level 4(Protection layer damaged) |
determining deterioration extent.

Based on the data collected from the cases analyzed, this study estimated the likelihood of repeat deterioration. After studying the cases and using CAD software to perform a statistical analysis, this study observed that the extent of deterioration mainly fell between 4% and 18%. For purposes of systematic identification, the author defined five deterioration ranges split throughout 0% to 15% (Table 4.).

The research bases for the evaluation of the impact on public safety are the degree of the impact on passers-by, building height and the width of adjacent roads. The building is deemed to have an impact on public safety if any one of these three criteria is satisfied. During the evaluation, evaluators considered whether pedestrian routes approach the "five foot way," whether the width of the sidewalk facilitates walking and whether building shrinkage has occurred (Table 5.).

### 3.2 Range of External Wall Tile Deterioration

Through a D.E.R. external wall tile visual diagnosis, the author computed condition indicators for the 46 case studies, and presented preliminary inspection results. These indicators allow us to understand the current condition of the external walls of a building. The Condition Index (CI) refers to the evaluated value of the external wall tile deterioration condition through visual diagnosis. The higher the CI value, the better the overall condition of the external wall. This study set limit values for the overall condition indicators, creating a range associated with maintenance and repair indicator considerations. If the building’s external wall aggregate is lower than the lower
limit of the range, a second diagnosis, and repair recommendation or renovation evaluation must be performed. The indicators can also be used to analyze the estimated useful life, and the CI value can be used for estimating the trend of external wall deterioration. Upon the completion of this evaluation and related calculations, the evaluators may make repair or renovation recommendations on external wall tiles that display conditions of serious damage or deterioration. This study adopts the external wall tile condition indicator equation proposed by Chiang (2014) and Guo (2011). Based on the actual condition, the calculation method and parameter definitions are adjusted to cater for future external wall tile evaluations. The adjusted equation is as follows:

\[
Cl = 100 - 100 \times \frac{(D + E) \times R}{(4 + 4) \times 4} \quad \text{…………(Equation 1)}
\]

Equation 1 derives the relative degree of the external wall tile inspected. The result ranges from 0-100, indicating the external wall tile health level. Zero indicates the lowest health level, while 100 indicates the highest. In Equation 1 herein, after the visual observation, the degree of deterioration (D) and the range of deterioration (E) were defined in this study, which is part of the description of the actual situation. Both D and E have consistent properties, on which the additive manner is applied. Because the R value has an influence on public safety, this study emphasized the importance of public safety. Therefore, the R value is calculated by multiplication. In Equation 1, the worst decision value of the DER was four for the visual diagnosis of the external wall tiles. This study includes all possible results of visual diagnosis into equation 1, resulting in 125 possibilities (D0–4× E0–4× R0–4=125). As the aim of the study is to facilitate a prompt judgment on old buildings that already have external wall tile deterioration, this research excludes those with 0 for deterioration degree, deterioration extent and impact on public safety, reducing the number of possible results to 64.

This study took the mean of the condition indicator result and moved one standard deviation in both directions to derive four ranges defining the diagnostic results. After the calculation, this study arrived at 125 possibilities, with a mean of 61.04 and standard deviation of 22.23. For easy categorization, the study used integers for the ranges, which follow: below 38; 39 to 60; 61 to 82; and above 83 (Fig.3.).

The focus of the study is public safety. Hence, the value of R indeed impacts the CI value results. After evaluating the 64 possibilities, the author then observe the CI value. If it falls within Grade 1, it indicates that the impact on public safety (R) is at its lowest and that both D and E values are good. In such a case, an annual inspection is sufficient. If the CI value falls within Grade 4, the impact on public safety is higher, and the D and E values are poor. In this case, this study would recommend an immediate external wall renovation. If the CI value falls within Grade 2 and 3 if the visual inspection is limited in its effectiveness of detecting external wall tile cavities or detachments, the result is a higher possibility of human error. This study recommend an inspection on external wall tiles at least once per year if R=1, as this value indicates a lower public safety impact. If R=2 or 3, indicating a higher public safety impact, this research recommend a tap tone diagnosis on part of the external wall (top and ground floor) to determine if cavity or detachment conditions are present. If R=4, indicating the highest impact on public safety, this research recommend an overall tap tone diagnosis of the external tiles of the building.

### 3.3 Statistical Analysis of Tap Tone Diagnosis

This study formulates a visual diagnostic method for external wall tiles. However, despite visual inspection advantages being low-cost and highly efficient, the visual (inspection) method has inherent shortcomings in that conclusions drawn from results are possibly overly subjective and overly lenient. Therefore, this study used sounding diagnosis to complement the visual diagnosis method. The tap tone diagnostic method is the most convenient, economical and widely used evaluation method for inspecting surface defects. Tile inspection is normally combined with other inspection methods (such as the visual inspection method) as a basis for inspection of the condition of wall tile deterioration.

The theory behind the tap tone diagnostic method is associated with determinations made through sound frequency. Besides pitch, sound also has intensity and tone. Generally speaking, pitch, intensity (loudness) and timbre are the three main elements of sound. The pitch of a sound is determined by its frequency of vibration. A higher frequency of vibration indicates a higher pitch, and a lower frequency of vibration indicates a lower pitch. The intensity of sound is determined by the vibration magnitude (amplitude) of the sound wave. Higher amplitudes equate to more powerful sound waves, and thus louder sounds. Observing the different sounds generated from
tapping on normal and deteriorated tiles with a tap tone diagnosis stick, this study uses a Fast Fourier Transform to determine a spectrogram. Frequency (Hz, x-coordinate) and amplitude (V, y-coordinate) are used to form the basis for determining the degree of tile deterioration. Spectrograms from the tap tone diagnosis are shown in Figs. 3. and Fig. 4. The spectrogram’s peak and trough for normal tiles show stable frequency (Fig. 4.), while deteriorated tiles show apparent instability (Fig. 5.).

This study investigated 46 building cases in National Taiwan University. Fig. 6. displays the diagnosis results: a total of 34 buildings, with CI values categorized into grades 2 and 3. This study used a lattice segmentation method for analyzing 177 tile deterioration image spectrums. Tables 6. and 7. display the 34 cases conducted, including two recording results among them.

This study ran the tap tone diagnosis on 34 buildings with CI values from visual inspections falling within Grade 2 and Grade 3 (four external walls for each building). This research found 177 areas of deterioration out of 680 tap tone diagnostic tests. This study deems the first peak of the spectrogram as noise, the beginning of the second wave as the start point of deterioration sound and its end point as the end point of the deterioration sound. The spectrogram is then segmented by lattice points. A further statistical analysis of the 177 deteriorated areas shows that the average start point of deteriorated tiles is 239Hz, while that for the end point is 761Hz. The deterioration extent is indicated by the shaded portion.

The study suggests that upon tap tone diagnosis, if the Fast Fourier Transform graph shows a frequency from 200 to 800 Hz, a cavity is likely in the tiles. If a tap tone diagnosis is required, the author suggest tapping at least 5 spots on the external wall to increase the overall detection accuracy. This study also tentatively recommend that if the tile deterioration ratio exceeds 50%, an immediate overall external wall renovation of the building should be performed. If the tile deterioration ratio is less than 50%, then safety measures to prevent surrounding objects from falling should be immediately imposed.

![Fig. 4. Transformed Spectrum for a Tap Tone Diagnosis on Normal Tile](image)

![Fig. 5. Transformed Spectrum for a Tap Tone Diagnosis on Deteriorated Tiles](image)

![Fig. 6. Forty-Six Cases Diagnosis Results of National Taiwan University](image)

### Table 6. Case A of Tap Tone and Visual Diagnosis Results

| Case A, CI = 53, Grade 3 (Attention needed) |
|-------------------------------------------|
| D  | E  | R  | CI Value |
| 1  | 4  | 3  | 53 |

Results of Case A tap tone test

![Graph showing the frequency response](image)
From the preliminary statistical results of this study, the following results can be found in the spectrum obtained from a fast Fourier transformation after the sounding diagnosis. For objects with obvious oscillating peaks in the frequency range between 200 Hz and 800 Hz on the spectrum, it can be concluded from a pullout test that most of those tiles had poor adhesion to the wall, leading to an increased likelihood of spalling.

This study suggested the following method to judge whether the tile deteriorated: After a sounding diagnosis, for a heterogeneous sound not easily judged from a deteriorating tile, a fast Fourier transformation can be applied to the spectrum. If the transformed frequency spectrum displays obvious oscillations in the range 200 Hz–800 Hz, then the object can be judged as an inferior tile. This study consolidates the results and recommendations for visual inspections and tap tone diagnoses and proposes a diagnostic criteria as well as standard operating procedures for the external wall tile deterioration diagnosis of Taiwan's buildings, as shown in Table 8. and Fig.7.

### Table 8. Public Safety Classification for Building External Walls Tiles

| Diagnostic Level | Method | Condition Index Classification | Determine the Grade | Proposed Renovation Principle |
|------------------|--------|--------------------------------|---------------------|-----------------------------|
| Stage 1          | D.E.R Visual Diagnostic Method | CI=63 | 1(Good) | Healthy, no immediate harm, regular checkup once a year |
|                  |        | 61≤CI≤82 | 2(Not bad) | R=1: check once a year. R=2,3: partial external wall tap tone diagnosis (top and ground floor) |
|                  |        | 38≤CI≤60 | 3(Attention needed) | R=4: comprehensive external wall tap tone diagnosis |
|                  | Tap Tone Method | CI<38 no significant peak frequency peaks between 240~760 Hz | 4(Bad) | R=2,3: partial external wall tap tone diagnosis (top and ground floor) R=4: comprehensive external wall tap tone diagnosis External wall renovation is recommended Check once a year Based on user demand, overall renovation |

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### 4. Conclusion and Recommendations

Since the construction boom in the 1970s in Taiwan, many buildings' external walls have suffered natural deterioration, and Taiwan has witnessed many incidents of external wall tiles falling, with some even resulting in fatalities. As the number of such cases has increased, a complete external wall tile diagnostic system is required. This study proposes public safety visual diagnostic models for external wall tiles of buildings. These models include D.E.R. visual diagnostic concepts, diagnostic content and diagnostic evaluation standards. It also offers a public safety grading system for external wall tiles, as well as suggesting the adoption of the tap tone diagnosis for tiles that can significantly impact public safety. This research also verified the developed evaluation model and proposed countermeasures as well as recommendations for deterioration conditions. The conclusion and recommendations of the study follow.

#### 4.1 Conclusion

The study establishes a D.E.R. visual evaluation model: "The visual diagnostic evaluation method..."
for external wall tiles of buildings”. This model for buildings' external wall tiles includes deterioration degree, deterioration extent and public safety impact (Degree, Extent, and Relevancy). Scores range from 0 to 4, 1 being optimal condition, and 4 being the worst condition. For a more accurate study of the condition of a building's external walls, this study established a D.E.R. visual inspection condition indicator (CI). Results can be categorized into four ranges, based on the mean and one standard deviation. Grade 1 is the best condition, while Grade 4 is the worst.

If the condition indicator is Grade 2 and R=1, this research recommend inspections at least once per year to reduce visual inspection errors. If R=2 or 3, this research recommend performing partial external wall (top floor and 1st floor) tap tone diagnoses. If R=4, an overall external wall tiles tap tone diagnosis should be performed. If the condition indicator is Grade 3, and R=2 or 3, this research recommend a partial external wall (top floor and 1st floor) tap tone.

Through visual diagnostic results, this study carried out tap tone diagnoses on 34 buildings. Frequencies between 200 and 800 Hz on the spectrogram imply a cavity is present in the tiles, and this can be used as a basis for determining tile deterioration.

4.2 Recommendations

The spectrum analysis results for the sounding diagnosis may not be the same for different types of tiles. This study suggested conducting experimental research on the common tile types (Rectangular Tile, Square Tile, and Small Tile) in Taiwan. Cross experimentation should also be carried out to account for variables to include the thickness, surfaces, and materials, as well as the different sizes, positions, and depths of the spalling, to compare their spectral patterns in sounding diagnoses.

The research recommends a review of existing laws and regulations to determine whether new provisions need to be added, whether the content of existing laws needs to be amended or whether a new regulatory approach should be adopted. As existing building laws in Taiwan lack relevant control regulations, the author recommend referencing the mandatory building inspection regulations of Hong Kong, a territory with a socioeconomic status similar to that of Taiwan Hong Kong regulations stipulate the mandatory inspection of public and private buildings that are more than seven stories high, have adjacent roads of 20 meters or wider and that are more than 20 years old because these buildings present a greater threat to public safety. As it is difficult to impose mandatory inspections on private buildings, the author recommend implementation beginning at the public level.

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