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Investigation of Factors Influencing Building Damage Due to Salt Attacks in the Tsunami-Affected Area of Banda Aceh City

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A R T I C L E I N F O

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A B S T R A C T

Salt attack is damage to building materials due to salt crystallization in pores, triggered by saltwater capillarity. In Banda Aceh, this risk increased after the 2004 tsunami. This study maps the distribution of salt attacks while assessing factors related to their intensity through the integration of field surveys, spatial analysis, and statistical analysis. The sample included 76 buildings showing symptoms of Salt attack. Descriptively, the height of the salt attack is in the range of 39–330 cm (average ±117.5 cm), the soil salinity level is 30–7420 ppm (median 366 ppm), while the TWI is generally moderate and the elevation is relatively low in the affected area. Because the data were abnormal, Spearman's correlation was used: high salt attack was positively and significantly associated with building age ($\rho=0.338$; $p=0.003$) and soil salinity ($\rho=0.340$; $p=0.003$). Other variables—TWI, elevation, coastal distance, drainage distance—were not significant at the level of the test used. Spatially, cases tend to be concentrated in tsunami-affected zones with lower elevations. The results of this study show that the age of buildings and soil salinity appear to be the most consistent factors related to the increase in salt attack height, while emphasizing the importance of moisture-salinity management and drainage improvement as mitigation directions in coastal areas.

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INTRODUCTION

The phenomenon of salt attack, also known as salt weathering, salt hydration distress, or salt crystallization, is damage that occurs to building materials due to salt crystallization (Young, 2008; Delgado et al., 2016). This process is caused by the crystallization of salts in the pores of materials such as bricks and plaster, which generates internal pressure and causes peeling, weathering, and disintegration of the surface layer (Delgado et al., 2016; Meilianda et al., 2022; Granneman et al., 2019). In the context of this study, the structural damage in question is not limited to the main elements such as beams or columns, but rather refers to the degradation of non-structural building elements such as brick walls, stucco, and surface coverings. Although classified as non-structural, damage to this part can degrade the functional integrity of the building and accelerate the overall deterioration. High salinity levels around buildings will aggravate damage due to the Salt attack phenomenon (Blackburn and Hutton, 1980; Agyekum et al., 2014)

The coastal area of Banda Aceh City is an area with a high risk of this phenomenon, especially due to the long-term impact of the tsunami of December 26, 2004. The 2004 Aceh tsunami caused damage to coastal land, including the accumulation of garbage, sediment, heavy metals, and other toxic pollutants that had a significant impact on soil salinity levels (Basri et al., 2011). The tsunami deposits worsen the physical condition of the soil and reduce the effectiveness of the natural desalination process, especially in areas with poor drainage and flat topography. Two decades after the disaster, salt residues in the subsoil are still found in high levels in some locations, indicating that the natural leaching process of salt has not been optimal, thus maintaining high salinity levels that favor the phenomenon of salt attack (McLeod et al., 2010; Rachman et al., 2008).

Although the phenomenon of salt attack and its impact on building structures has been widely discussed in studies and various studies, it is still limited that highlights the relationship between the distribution of salt attack and post-tsunami environmental factors. For example, previous studies have emphasized the effect of salinity on the durability of building materials in general (Gentilini et al., 2012; Mazer et al., 2020), but have not explored in detail the influence of geographical and hydrological variables in the context of tsunami disasters, such as in Banda Aceh City.

This study aims to decipher the relationship between soil salinity levels, building age, and other factors in relation to the Salt attack phenomenon, with the main focus on tsunami-affected zones in Banda Aceh City. This study will map the distribution of the Salt attack phenomenon to parameters such as coastline, and topographic humidity index. The Spatial Analysis of the Topographic Wetness Index (TWI) in this study will be used to identify potential areas of tsunami sediment traps which will be used as one of the parameters in this study. Using statistical methods such as correlation and linear regression, this study seeks to identify the parameters that have the most influence on the occurrence of the Salt attack phenomenon, so that it can be the basis for developing effective mitigation strategies to protect buildings from the long-term impacts of tsunami disasters.

THEORETICAL REVIEW

Salt Attack

Salt attack is a form of degradation of building materials, which is caused by the crystallization of salts in the pores of the material. This process begins with the penetration of water containing salt into porous materials such as bricks or mortar through a capillary mechanism. When the water evaporates, the salt is left behind and crystallizes, resulting in crystallization pressures that are capable of damaging the integrity of the material (Doehne, 2002; Delgado et al., 2016). The salt crystallization pressure can reach 20–100 MPa, far exceeding the tensile strength of conventional plaster mortar (Steiger, 2005; Flatt and Scherer, 2008). The repeating soluble–crystal cycle enlarges micro-cracks and allows deeper moisture penetration, thereby accelerating the accumulation of salt in the top layer of the wall.

The crystallization of this salt not only results in the appearance of salt deposits on the surface (efflorescence), but it can also damage the internal tissues of the material which has an impact on peeling, fine cracks, and heavier structural damage. This phenomenon often occurs in buildings that are in environments with high salinity levels, high humidity, and poor air circulation.

Factors Causing Salt Attack

Salt attacks are strongly influenced by soil salinity and groundwater, which can increase significantly due to disasters such as tsunamis. High air humidity, wet-dry cycles, and poor drainage systems also accelerate the process of salt absorption and deposition in building walls (Nosetto et al., 2013; McLeod et al., 2010).

The use of porous materials without a moisture protection system such as Damp Proof Course (DPC), as well as the absence of waterproofing, makes building walls very vulnerable to salt water penetration (Gonçalves et al., 2009; Mydin et al., 2017). The durability of materials to salt attack decreases exponentially as the building ages due to the reduced ability of pores to withstand crystallization pressure (Granneman et al., 2019). Old buildings that do not have a damp proof course have a higher risk of moisture migration from the ground. In addition, inefficient drainage systems in urban environments extend the retention time of saltwater around the foundation (Philip Gassa et al., 2025), thereby accelerating the capillarity process and salt cycle.

Inadequate construction quality, selection of materials that are not resistant to aggressive environments, and lack of building maintenance, are additional factors that accelerate the occurrence of damage due to salt attacks. The study of Meilianda et al. (2022) in the coastal area of Banda Aceh also showed that tsunami deposits worsened soil conditions and accelerated the process of building degradation.

Therefore, this study will include additional variables (drainage conditions, piping conditions, initial land conditions, and soil technical treatment) as potential factors that affect salt attacks. These variables are recorded during the field survey and will be evaluated along with other factors to understand their role in the Salt attack phenomenon.

Soil Salinity

Groundwater and soil salinity refers to the concentration of dissolved salts in groundwater and soil. This phenomenon is a serious concern, especially in arid and semi-arid climates, as it can have a significant impact on soil quality, agricultural productivity, and structural stability (Krishan, 2019).

Human activities greatly affect the salinity dynamics of groundwater and soil. Irrigation with low-quality water can increase soil salinity, while excessive use of groundwater in coastal areas can lead to intrusion (Mirzavand et al., 2020). The relationship between groundwater and soil salinity also shows significant spatial and temporal variations, influenced by factors such as topography, seasonal changes in rainfall, and evaporation rates (Nosetto et al., 2013).

The impact of high salinity on groundwater and soil can be very detrimental, including decreased agricultural productivity and damage to building infrastructure through processes such as salt attack and rising damp (Young, 2008). This phenomenon is of particular concern in areas affected by natural disasters such as tsunamis, where seawater intrusion can drastically alter soil salinity and groundwater salinity conditions in a short period of time (Basri et al., 2011). Climate, topography, and land use are important factors that affect salinity patterns accompanied by poor draenase systems further worsening the salinization process.

METHODOLOGY

Data Sources and Types

The primary data in this study is in the form of direct measurements and interviews with owners, land, and buildings that are indicated to experience the Salt attack phenomenon. Meanwhile, data such as damage repair efforts, technical treatment of the soil, and other factors are optional depending on the respondent's knowledge in answering them.

Table 1. Sources and types of research data

Yes	Variabel	Data Source	Tools/Methods	Data Type
1	Tinggi *Salt attack*	Measurement	Meteran	First
2	Distance of Building Location to Coastline	Spatial Analysis	GIS	First
3	Topographic Wetness Index (TWI)	Spatial Analysis	GIS	First
4	Until Salinitas Tanakh	Measurement	EC Meter	First
5	Administrative boundaries of Banda Aceh City	Bappeda (2018)		Seconds
6	Banda Aceh City coastline data	BIG		Seconds
7	Digital Terrain Model of Banda Aceh City	JICA (2005)		Seconds

Research Object

(Ikhsan, 2022) Salt attack in the area of the Aceh Tsunami landslide on December 26, 2004. From the results of previous research in 2022, several cases were found (Ikhsan, 2022) Salt attack occurred in the area where the 2004 tsunami waves stopped or in the highly affected urban area zone and affected urban area of the 2004 tsunami damage map by ICube-SERTIT on January 4, 2005, this is suspected to be an indication of ineffective desalination in the area. The two zones are located in the Jaya Baru, Bandar Raya, Kuta Alam, Lueng Bata, Syiah Kuala, and Ulee Kareng Districts. The determination of the location of the building to be measured and observed is one that visually experiences the Salt attack phenomenon.

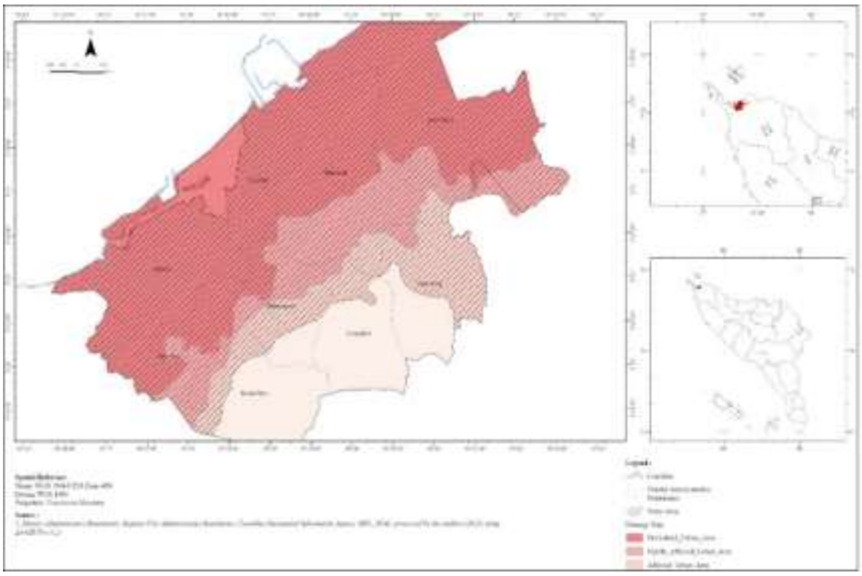

Figure 1. Map of the location of the research object

Stages of Data Analysis and Processing

The data analysis stage in this study is divided into three main parts, namely spatial analysis, descriptive analysis of survey data, and advanced statistical analysis. Each part supports each other to identify the pattern of the spread of the Salt attack phenomenon and the factors that affect it as a whole. Here is an explanation of each stage:

Descriptive Analysis

Before the statistical test was carried out, a descriptive analysis of the survey data was first carried out. This stage serves as an initial exploration to understand the characteristics, distribution, and validity of field data. Numerical data such as salt attack height, soil salinity level, and building age were summarized through concentration and dispersion measurements, along with frequency distribution.

The results of this descriptive analysis act as an initial validation, as well as provide an overview of the general pattern of the data. Thus, the descriptive analysis answers the initial question of "how the characteristics of the data are collected", before proceeding to the analysis of the relationship between variables

Statistical Analysis

Statistical analysis was carried out to test the relationship between variables and determine which factors had the most influence on the height of salt attack. The statistical analysis carried out includes: (1) prerequisite test (assumption) of data, (2) correlation analysis, (3) linear regression analysis. This sequence is designed in such a way that the results of one stage can provide information or input for the next.

Correlation Analysis

To explore the two-way relationship between variables, correlation analysis was performed. The correlation technique used adjusts the data type of each variable. For ordinal-scale variables or if the assumptions of linearity and normality are not met, Spearman's correlation (Spearman's rho) is used as a non-parametric alternative. The results of the correlation analysis will be in the form of a correlation matrix that shows the correlation coefficient (r) between each pair of variables and their significance (p-value). The r-coefficient is valued between -1 to +1; A positive value signifies a unidirectional correlation, a negative in the opposite direction, and an absolute value greater than 1 signifies a stronger linear relationship. Significance (p-value < 0.05) indicates the relationship is statistically convincing. These correlation findings are an early indication of the influence of each variable and also help detect the problem of multicollinearity between independent variables (if two independent variables turn out to be very highly correlated with each other).

Linear Regression

This stage serves to find out which variables are not significant and most likely irrelevant in multivariate models and significant variables. The process is run with statistical software (e.g. SPSS) through the Linear Regression procedure, with the initial interpretation focused on the Coefficients and ANOVA tables (a test of the significance of the coefficient and magnitude of R^2).

RESEARCH RESULTS

Age of the Building

The distribution of building ages at the study site showed that most of the buildings were built before the 2004 tsunami, which was 55 units (72.4%), while buildings built after the tsunami amounted to 21 units (27.6%). The pre-tsunami predominance of buildings suggests that many residences in the affected areas still retain old construction, with a longer level of exposure to post-tsunami environmental conditions.

If reviewed in more detail, the variation in the age of the building shows a range between 11 and 75 years, with a fairly variable distribution pattern between samples. Some buildings that are more than 40 years old show a higher level of susceptibility to the phenomenon of salt attack, in line with the longer the accumulation of salt crystallization in the wall material. On the other hand, buildings erected after the tsunami are relatively younger, but still have the potential to suffer damage if they are built on land with high salinity levels and inadequate drainage systems.

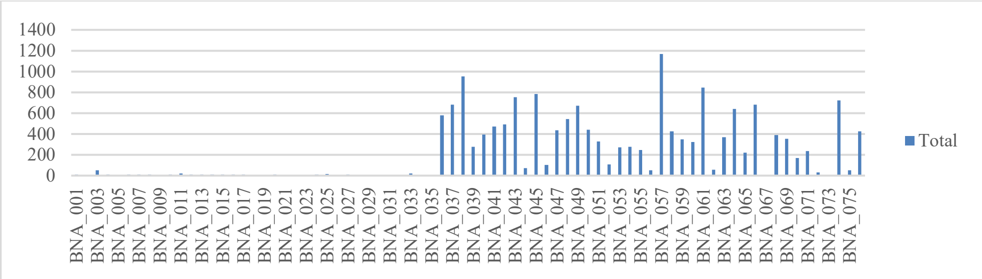

Figure 2. Building Age (Numeric)

Drainage Distance

The drainage distance variable in buildings shows a fairly wide variation, with a range of values ranging from 0.25 meters to 11.7 meters. The average drainage distance is 5.0 meters, with most buildings being in the medium distance range between 3 to 8 meters from the drainage channel. This condition shows that there is a difference in the access of each building to the drainage function in its environment.

Buildings located close to drainage channels have the potential to undergo a natural leaching process of salt accumulated in the soil more quickly, so that the salinity level of the soil around the building can be reduced over time. On the other hand, buildings that are farther away from drainage channels tend to have a greater risk of salt accumulation, as the processes of groundwater circulation and surface flow become less effective.

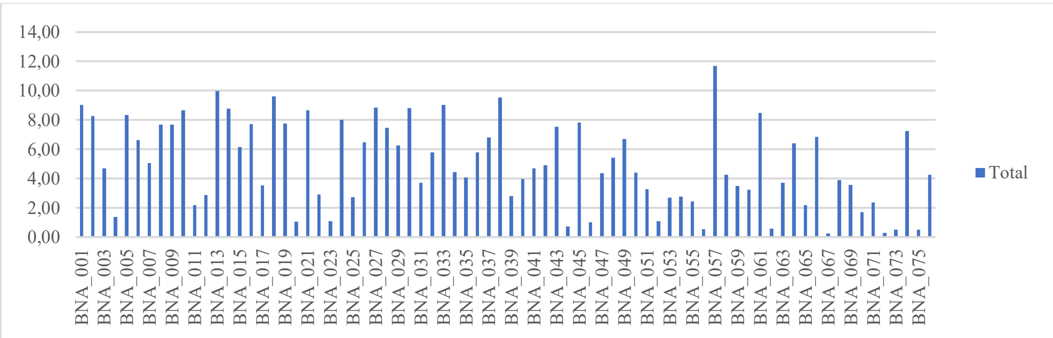

Figure 3. Drainage Distance

Soil Salinity Levels

The soil salinity level at the research site has a very wide range, ranging from 30 ppm to 7420 ppm, with an average of 965 ppm. A median value of 366 ppm indicates that most of the samples are in the low to medium salinity category, but there are some measurement points with extreme values that indicate very high salinity levels. This condition reflects the heterogeneity of land due to differences in soil type, proximity to the coast, and tsunami sediment residues.

The distribution of the graph shows the concentration of high salinity values at certain points, especially in locations in the Highly Affected Urban Area and Devastated Urban Area zones. This corresponds to the characteristics of posttsunami regions, where seawater intrusion and sediment accumulation lead to high salt levels in the soil. In contrast, some points with low salinity are generally located on land with better drainage conditions or locations relatively far from the coastline.

The high salinity value increases the potential for the movement of saltwater capillaries into the wall material, thereby accelerating the crystallization of salts that damage the surface and non-structural structures of the building.

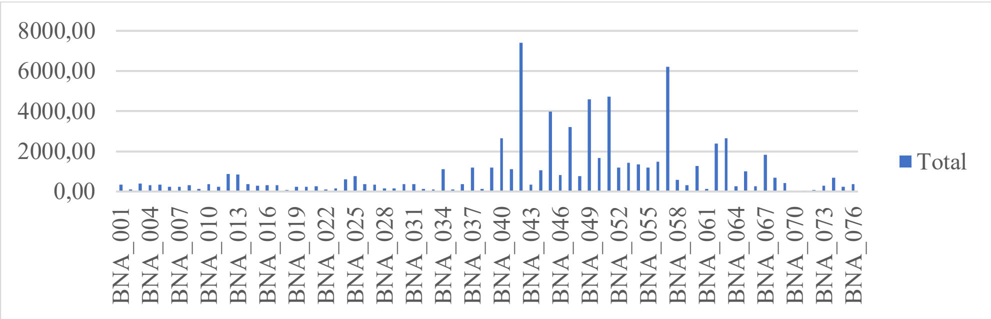

Figure 4. Soil Salinity Levels

High Salt Attack

The measurement results showed that the height of the Salt attack on the walls of the building had a significant variation, with a range between 39 cm to 330 cm. The average value of 117.5 cm and the median of 114.5 cm show that this phenomenon generally occurs up to ±1 meter above the floor surface, although in some extreme cases it can reach more than 3 meters.

Buildings with relatively high salt attack values are generally located in areas with greater soil salinity levels and poor drainage conditions, so that the process of salt water movement through capillarity becomes more dominant. On the other hand, buildings with relatively low values tend to be located on land with good drainage or closer proximity to waterways, allowing for a natural leaching process of salt.

The higher the traces of salt attack on the wall, the greater the non-structural damage that can occur, from efflorescence to peeling off the plaster layer and the potential disintegration of wall materials.

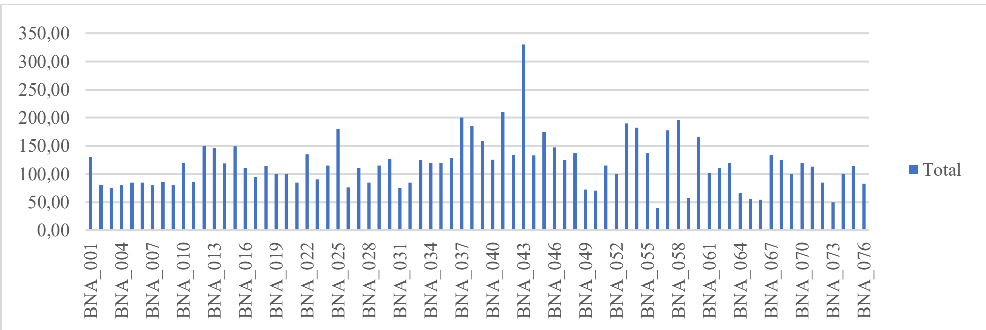

Figure 5. High Salt Attack

Topographic Wetness Index

The analysis results show that the Topographic Wetness Index (TWI) values at the study sites ranged from 5.59 to 20.20, with an average of 9.55. Most buildings fell within the mid-range, between 8 and 12, while only a small number showed extreme values above 15. This distribution pattern indicates that the majority of buildings are located in areas with moderate wetness levels, but certain locations still tend to be wetter and potentially retain water accumulation.

A high TWI indicates a tendency for water accumulation on land with relatively flat or concave topography, resulting in a slower natural salt leaching process. This condition increases the likelihood of saltwater intrusion into the soil and increases the risk of salt attack on buildings. Conversely, a low TWI is generally found on land with steeper slopes, where surface runoff more quickly reduces the salt content in the soil.

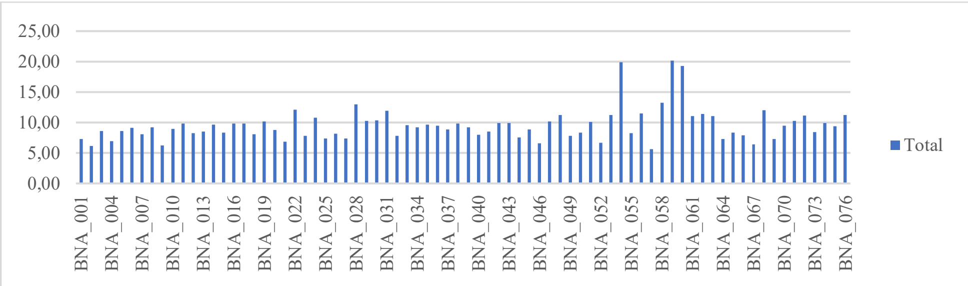

Figure 6. Topographic Wetness Index (TWI)

Building Location Elevation

Based on the results of elevation data analysis, the buildings at the research site have a relatively low height to sea level, with a value range between 0.82 meters to 5.6 meters. The average elevation was recorded at 2.24 meters, while most buildings were concentrated at heights between 1 and 3 meters above sea level. This distribution illustrates that the majority of buildings are in coastal lowlands which are areas directly affected by the 2004 tsunami waves.

Buildings with lower elevations tend to be more susceptible to the accumulation of saltwater and tsunami sediments, so the salinity levels of the surrounding soil are relatively higher. This condition increases the chance of salt attack, because high soil moisture accelerates the process of capillarity of salt water towards the building wall. In contrast, buildings with higher elevations (above 4 meters) generally have a lower risk, as surface flow and gravity facilitate the natural leaching process against salt.

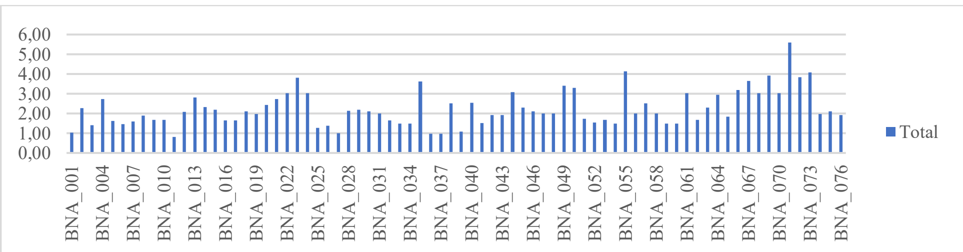

Figure 7. Building Location Elevation

Distance of the Building to the Beach

The results of the analysis showed that the distance of the building from the coastline varied quite widely, with a range between 367 meters to 4376 meters. The average distance is recorded at 2832 meters, while most of the buildings are concentrated in the range of 2000 to 3500 meters from the coastline. This variation illustrates the difference in the level of exposure of buildings to seawater intrusion and saltwater humidity in the study area.

Buildings that are closer to the shore (<1000 meters) generally face a higher risk of seawater intrusion, salty air humidity, and the potential for salt accumulation in the soil. This condition can accelerate the occurrence of salt attack, especially when combined with an inadequate drainage system. In contrast, buildings farther from the coast (>3000 meters) are relatively lower at risk, although other environmental factors such as soil type and TWI values can still affect the level of vulnerability.

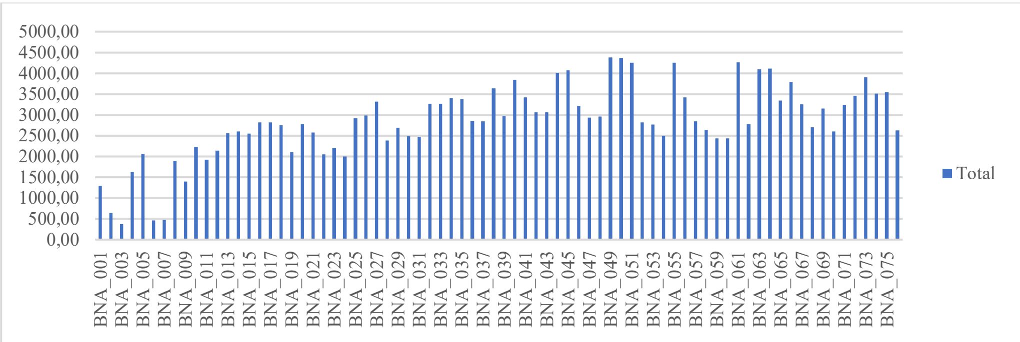

Figure 8. Distance of the Building to the Beach

Based on the results of the descriptive analysis, it can be concluded that the majority of the buildings observed are permanent buildings as a result of personal initiative, with the predominance of the age of buildings that have been established before the 2004 tsunami. Land conditions are mostly in the form of heaps, but there are still other variations such as former swamps, garden soils, and tsunami deposits that have direct implications for salinity levels. Drainage and piping systems work relatively well in most buildings, although leaks and flow limitations are still found.

Most of the buildings are in the Highly Affected Urban Area and Devastated Urban Area zones, with a TWI value indicating a tendency to inundation, an average low elevation of 2 meters above sea level, and a distance to the beach that varies from hundreds of meters to more than 4 km. These factors together form a picture of the vulnerability of buildings to the phenomenon of salt attack, which is reflected in the average height of the salt attack footprint of 117.5 cm.

Correlation Analysis

Before the regression analysis was carried out, the Spearman correlation test was first carried out to see the relationship between the research variables and the phenomenon of high salt attack in buildings. The selection of the Spearman test was based on the results of a prerequisite test that showed that the data did not fully meet the assumptions of normality and linearity, so the use of Pearson correlation was inappropriate. Spearman correlation is a non-parametric method that measures the relationship between variables based on ranking, making it more suitable for data that are not normally distributed or contain outliers (Pandey, 2020).

Table 2. Correlation Analysis

			High *Salt attack*	**Age**	**Soil Salinity Levels**	**TWI**	**Elevation**	**Beach Distance**	**Draenase Distance**
Spearman's rho	Tinggi *Salt attack*	Correlation Coefficient	1	.338**	.340**	0.142	-0.099	0.071	0.062
		Sig. (2-tailed)	.	0.003	0.003	0.222	0.392	0.54	0.592
		N	76	76	76	76	76	76	76

****. Correlation is significant at the 0.01 level (2-tailed).**

Based on the Spearman's rho test (n = 76), the height of salt attack showed a significant positive correlation with the age of the building (ρ = 0.338; p = 0.003) and soil salinity level (ρ = 0.340; p = 0.003). This positive direction means that the increase in the age ranking and the increase in the soil salinity ranking tend to be followed by an increase in the ranking of salt attack height. The magnitude of the coefficient (≈0.34) indicates a moderate association—consistent enough to support the hypothesis, but still leaves room for other factors that have not yet been observed. These results are consistent with field findings and the posttsunami Banda Aceh context, where salt residues in soil/groundwater persist for a long time and older buildings experience longer periods of exposure (Meilianda et al., 2023).

Thiscan be explained by the capillary–evaporation–crystallization cycle: the salt solution migrates to the pores of the walls through the action of capillaries, then as the water evaporates, the salts settle and crystallize generating crystallization pressures that damage the plaster/brick. The intensity of damage increases with the length of exposure (age) and the amount of salt availability (salinity) (Doehne, 2002; Espinosa-Marzal & Scherer, 2010; Delgado et al., 2016; Guimarães et al., 2016; Franzoni, 2018; Granneman et al., 2019). Thus, the age of the building and the intensity of saline play a role as the main risk factors in the humid coastal environment and in the sites that store the post-tsunami salt heritage.

In contrast, TWI showed a positive but weak and insignificant correlation (ρ = 0.142; p = 0.222), a weak and insignificant negative elevation (ρ = − 0.099; p = 0.392), while distance to shore (ρ = 0.071; p = 0.540) and distance to drainage (ρ = 0.062; p = 0.592) were also positive and insignificant. The direction of this sign remains informative: the negative trend of elevation suggests that lower locations are potentially more vulnerable, while the positive trend of TWI/shoreline/drainage has not been statistically strong enough in this sample. Substantively, insignificance can be influenced by (i) the homogeneity of the elevation range and distance within the study area; (ii) the dominance of salinity factors that mask the effect of macro moisture proxy (TWI/elevation) (Beven &

Kirkby, 1979); and (iii) tsunami salt sediment residues that extend so far inland that simple proximity to the coastline does not necessarily represent actual saline intensity.

Implicitly, mitigation strategies and repair priorities should be focused on older buildings that stand on high salinity soil, while assessing factors of material/plaster type, quality of care, and local drainage function. These findings are consistent with the theoretical framework of salt weathering in humid coastal environments (Delgado et al., 2016; Franzoni, 2018; Granneman et al., 2019) and the post-tsunami context of Banda Aceh (Meilianda et al., 2023).

Analysis of the Regresi Lineman

Linear regression analysis was carried out to determine the direction and strength of the relationship between each independent variable and the dependent variable in the form of high salt attack. This test was carried out for six main variables, namely the age of the building, soil salinity level, topographic wetness index (TWI), elevation (DEM), distance of the building to the coastline, and the distance of the building to the drainage channel.

Age of the Building

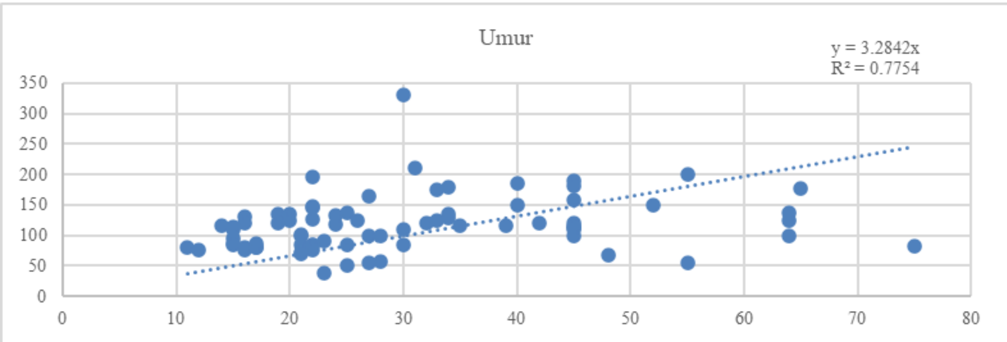

Figure 9. Scatterplot Age of the Building

The scatterplot between the age of the building and the height of the salt attack shows a clear positive linear pattern . The regression line on the graph is constrained without interception (through the origin point) with the equation ŷ = 3.2842x and R^2 = 0.7754. This means that about 77.5% of the variation in salt attack height can be explained by the age of the building. In practical terms, the slope coefficient of ~3.28 cm/year indicates that each additional year of building age is associated with an increase in the height of the salt attack zone of about 3.3 cm.

The selection of regression without interception is based on physical considerations: at the time of the new building (age = 0), the accumulation of salt crystals on the walls has not theoretically been formed, since the process takes time and repeated capillary–evaporation–crystallization cycles (Delgado et al., 2016; Franzoni, 2018; Granneman et al., 2019). Therefore, the initial condition is reasonably taken close to 0 cm so that the regression line is tied to the point (0.0).

Although the trend is strong, the dot spread still shows variation and some outliers. This indicates the influence of other variables—such as soil salinity level, rising damp (TWI/elevation), material type, and treatment—that will be evaluated in the next stage of multivariate analysis.

Soil Salinity Levels

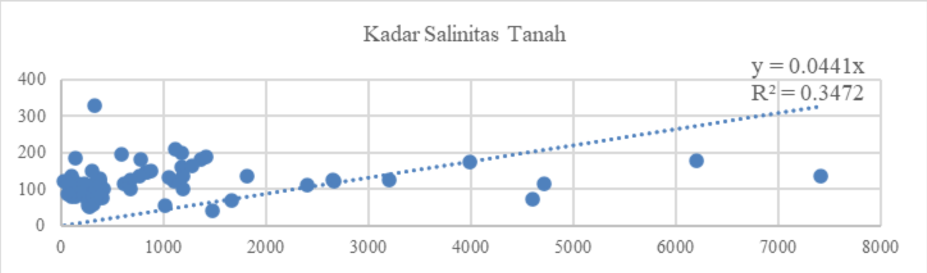

Figure 10. Soil Salinity Level Scatterplot

The scatterplot between soil salinity and salt attack height shows a positive linear trend. The regression line in the intercept graph crosses the zero line with the equation $\hat{y} = 0.0441x$ and $R^2 = 0.3472$. This indicates that approximately 34.7% of the variation in salt attack height can be explained by differences in soil salinity; the remainder is influenced by other factors such as humidity/rising damp (TWI/elevation), material type, and building maintenance. Practically, a slope of 0.0441 cm per ppm means that an increase of approximately 1,000 ppm salinity is associated with an increase in salt attack height of approximately 4.4 cm.

The choice of the model without an intercept is based on a physical argument: if salinity = 0 (and other factors are held constant), there is practically no source of salt for crystallization in the pore walls, so the theoretical salt attack zone height approaches 0 cm. The deterioration process itself requires dissolved salts to migrate with moisture, then evaporate and crystallize, generating crystallization pressure in the plaster/brick (Delgado et al., 2016; Franzoni, 2018; Granneman et al., 2019).

The distribution of points is quite wide and there are outliers (e.g., high salinity but relatively low elevation), indicating the influence of other controlling variables (local drainage, wet-dry intensity, material properties, distance from the coast). Therefore, these findings will be strengthened in subsequent multivariate/robust analyses to increase the model's explanatory power.

- Topographic Wetness Index (TWI)

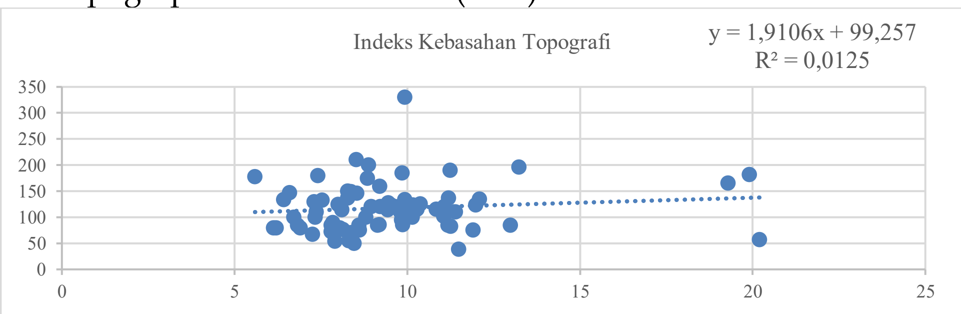

Figure 11. Topographic Wetness Index (TWI) Scatterplot

The TWI scatterplot with High Salt attack shows randomly scattered dots without a clear linear pattern. There is no consistent trend of increasing or decreasing, so it can be concluded that the relationship between these two variables is non-linear. This indicates that TWI's role in the Salt attack phenomenon may be more complex, influenced by interaction factors with other variables such as soil type or drainage conditions. Figure 11 shows the relationship between the topographic wetness index (TWI) and the height of the salt attack, with a positive but very weak relationship direction, having an equation $y = 1.9106x + 99.257$ and $R^2 = 0.0125$. This shows that the TWI value only explains about 1.25% of the variation in the height of the salt attack, so the topographic humidity level does not have a major effect directly on building damage. However, areas with high TWI values remain potentially moist and support groundwater accumulation (Beven & Kirkby, 1979).

- Building Elevation

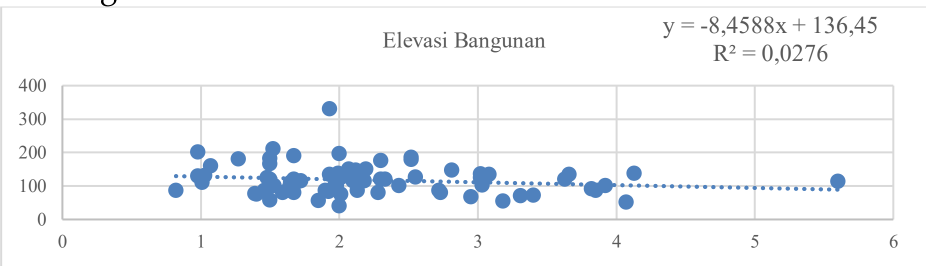

Figure 12. Building Elevation Scatterplot

Scatterplots of elevation with High Salt attacks also show random patterns. There is no consistent trend of linear relationships, although there are indications that buildings at very low elevations tend to have higher salt attacks. This relationship is weak, indicating that elevation itself does not directly determine the height of salt infestation, but rather interacts with other environmental conditions. Figure 12, the building elevation variable shows a negative relationship with the height of the Salt attack with the equation $y = -8.4588x + 136.45$ and $R^2 = 0.0276$. This value indicates that the lower the elevation of a building, the more likely it is to have a salt attack. This condition is consistent with the results of research by McLeod et al. (2010) and Basri et al. (2011) which stated that lowland areas tend to maintain higher salt levels because the natural washing process (desalination) takes place more slowly.

- Distance of Building to Coastline

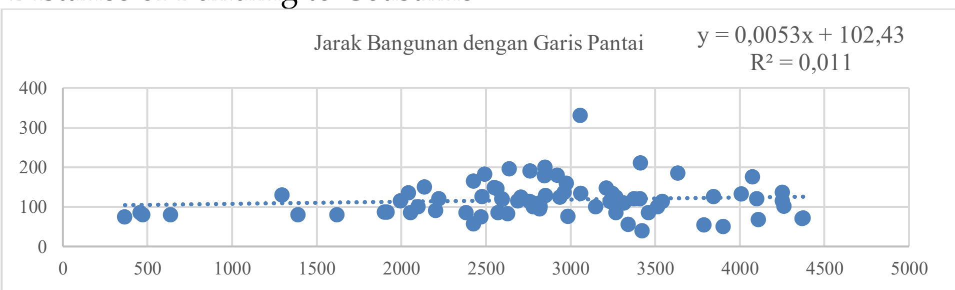

Figure 13. *Scatterplot* Distance of Buildings to Coastline

The scatterplot of the distance to the beach with the height of the salt attack shows a non-linear distribution of points, where the height of the salt attack does not necessarily decrease in buildings farther from the shore. This condition can be caused by a variety of local factors, such as differences in soil type, drainage conditions, and the effects of tsunami deposits that are not uniform throughout the region. Then, Figure 13, shows the relationship between the distance of the building to the coastline and the height of the salt attack, which shows a very weak positive direction with the equation y = 0.0053x + 102.43 and R^2 = 0.011. A low determination value indicates that distance from the coast is not a major factor determining the extent of Salt attack damage. This condition can be caused by local variations such as surface flow direction, topographic differences, and uneven residual tsunami deposits in the field (Ghiffari, 2020).

- Building Distance to Drainage

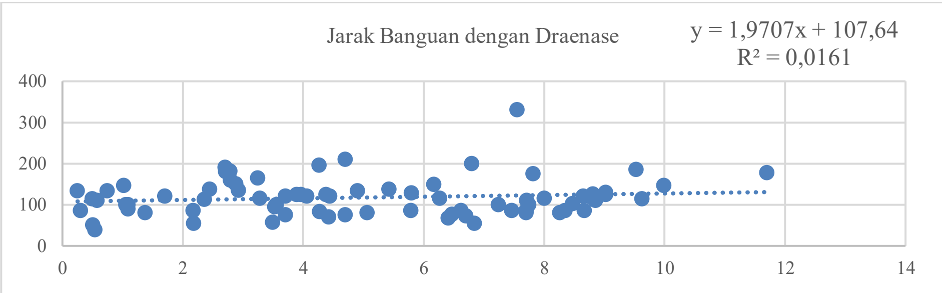

Figure 14. Scatterplot Building Distance to Drainage

The scatterplot of drainage distance with High Salt attack shows a weak positive directional tendency. Buildings that are located further away from drainage tend to have greater salt infestation heights. This is understandable because close drainage allows for natural leaching of salt in the soil, while distant drainage makes salt accumulation more difficult to reduce. Although the pattern is not very strong, the direction of the relationship still shows positive linear potential. Figure 14, illustrates the relationship between the distance of the building and the drainage channel to the height of the salt attack, with the equation y = 1.9707x + 107.64 and R^2 = 0.0161. This value suggests that about 1.6% variation in the height of the salt attack can be explained by the distance to drainage. The direction of this positive relationship indicates that buildings farther away from the drainage channels tend to have higher soil moisture levels, which can accelerate the process of salt crystallization on the walls (Nosetto et al., 2013).

Overall, the results of the linear management analysis showed that only a few variables showed a tendency to have a positive linear relationship with High *Salt attack*, especially Building Age, Soil Salinity Level, and Drainage Distance. Meanwhile, the TWI, Elevation, and Distance of Coast variables show a random distribution of data without a clear linear pattern. Thus, the assumption of linearity is only partially fulfilled, but linear regression is still possible, as well as considering the possibility of non-linear relationships or interactions between variables.

Spatial Analysis

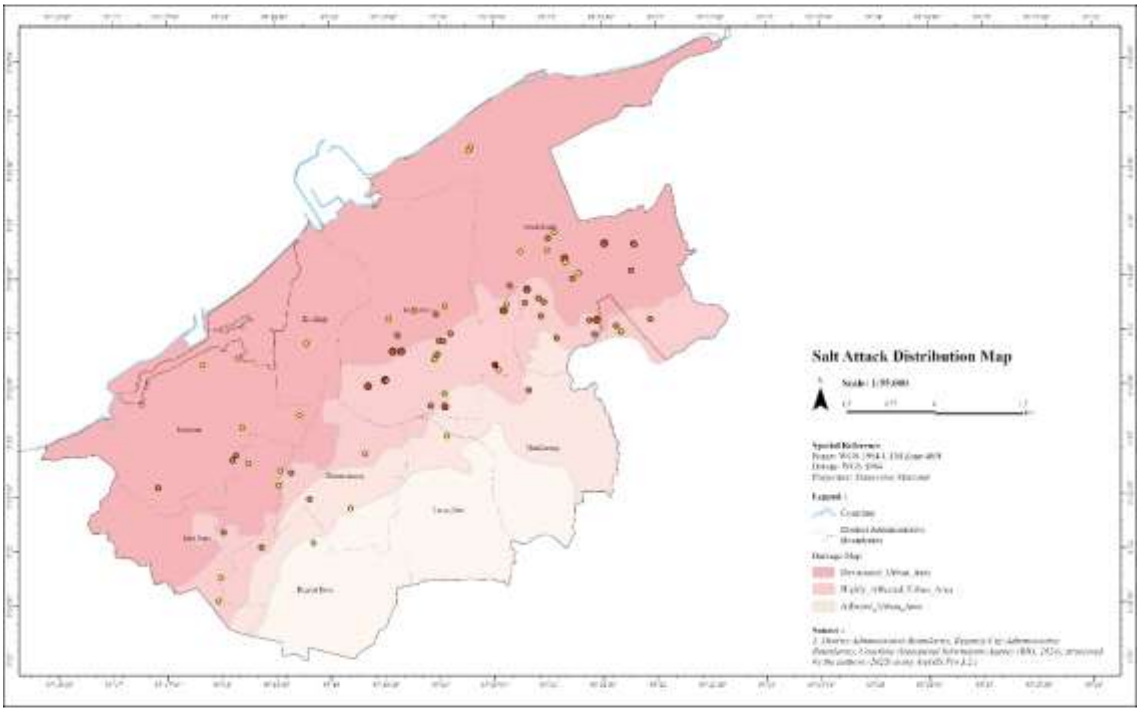

Figure 15. Map of the Distribution of the Salt Attack Phenomenon

This map shows the distribution of measured building points (circle symbols) that overlap with the 2004 tsunami impact zone (Affected–Highly Affected–Devastated Urban Area). The spatial pattern is clear: the larger salt attack height clusters are concentrated in three coastal districts—Meuraxa, Kuta Alam, and Syiah Kuala—that are in/adjacent to the Highly–Devastated Urban Area class. The altitude tends to decrease to the south-southeast (Baiturrahman, Jaya Baru, Ulee Kareng, Lueng Bata, Banda Raya) which is relatively farther from the coastline and higher in elevation. This transition forms a coastal–land gradation consistent with traces of inundation and posttsunami saline deposits.

In process, the pattern makes sense: salt residues in the soil/groundwater in coastal lowlands—plus capillarity and wet–dry cycles—encourage the migration of saline solutions from the foundation to the walls, then crystallize in the evaporation zone which generates crystalline pressure and increases the zone of deterioration (rising damp). Environments with higher soil salinity and moisture availability (less effective drainage, high TWI, low elevation) accelerate accumulation, so that buildings in these areas show a more dominant salt attack height than the drier/higher downstream-land areas (Delgado et al., 2016; Franzoni, 2018; Granneman et al., 2019). In Banda Aceh, salt heritage from inundation/tsunami spray has been reported to be persistent in shallow soils, especially in coastal lowland alluvial zones so that the risk of degradation of building materials persists in the long term (Basri et al., 2011; Meilianda et al., 2022).

In closing, the map confirms that the salt attack hotspots are concentrated in the west-east coastal corridor—Meuraxa to Kuta Alam and Syiah Kuala—which overlap with the highest tsunami impact zone, then gradually decrease in intensity to the inner districts of the city (Jaya Baru, Ulee Kareng, Lueng Bata, Banda Raya). However, local variation is still visible: a number of points in the high-impact zone actually show medium or low elevation, indicating the role of microfactors such as the type of material/plaster, quality of treatment, microelevation, and drainage conditions of the site. This pattern is consistent with the statistical findings that building age and soil salinity are positively associated with salt attack height, while also suggesting the need for advanced multivariate analysis—including TWI/elevation, coastal distance, material type, and maintenance practices—to improve model clarity and more robustly deconstruct the influence of each factor.

CONCLUSIONS AND RECOMMENDATIONS

Correlation Test

Overall, the correlation test confirmed that the height of salt attack was primarily influenced by the age of the building and soil salinity—both positively directional and meaningful—while the moisture/site position proxies such as TWI, elevation, coastal distance, and drainage distance does not show a convincing relationship. These findings place exposure age and copy intensity as key factors, so mitigation strategies should prioritize older buildings in locations with high salinity, along with moisture management and material treatment at site level.

Regression Analysis

Although there were no statistically significant variables, theregression results showed a positive directional coefficient for building age and soil salinity, both of which were most consistent with the increase *in salt attack* height. The distance to drainage is also positive but weak, the elevation is negative, while the TWI and distance to the shore show a very weak/unclear positive tendency in this data range.

FURTHER STUDY

Further research is needed by adding variables such as wall material type, groundwater level depth, micro-drainage conditions, and building maintenance patterns, as well as using MFA or SEM approaches to capture more complex interfactor relationships.

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