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Effects of Storm Surge on Vapor Explosion in the Steel Mill Industry

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ABSTRACT

Industrial disasters caused by natural disasters have simultaneously occurred in many cases. Accordingly, it has been pointed out that the risk of potential secondary composite disasters caused by the natural disasters should be analyzed. Especially, steel mills which are usually located near coasts, are exposed to a vapor explosion due to wet conditions caused by storm surge while manufacturing and transporting the molten metal. This study was aimed to predict and to analyze the risk in terms of the vapor explosion in a steel mill industry caused by the storm surge. Frequency referred to likelihood that a hazard will occur, was estimated for the reason that the risk is defined as the product of the frequency and consequence. And then, simulation was performed by using program COAST which is the tool to estimate coastal adaption to sea-level rise. Through this procedure, the flood-affected areas were confirmed to be spatially consistent with the manufacturing and moving paths of the high-temperature molten metal. The results showed that several spots, first flooded at the 10-year return period in 2016, rapidly expanded when using the 100-year return period in 2036. In the hazard areas where a vapor explosion may occur, flood-affected areas with 50-year, 100-year, and 200-year return periods in 2066 expanded drastically. This information can be used to provide preliminary knowledge on storm surge flooding prone areas in the steel mills so that the secondary composite disasters such as the vapor explosion could be prevented.

KEYWORDS –Risk assessment, Tide level frequency, Frequency analysis, COAST, Mitigation plan

I. INTRODUCTION

Vapor explosion which may take place when high-temperature molten metal contacts water vapor, is one of the considerable accidents in steel mill industries. In other words, the vapor explosion is a physical phenomenon that causes extreme boiling by rapid heat transfer from molten metal to moisture in the storage vessel or on the bottom of dry pit (Berthoud, 2000; Eckhoff, 2016; Taleyarkhan, 2005). It caused by moisture in the floor which is not sufficiently dried while manufacturing and transporting the molten metal. The vapor explosion has occurred more than once every year(Choi, 2013; Kim, 2013). In heavy rain period of July 2013, it was reported that the vapor explosion occurred in a major Korean steel mill, POSCO located in Pohang, South Korea due to the surface retention of the impermeable layer by contact high-temperature molten metal and water as shown in **Figure 1**(Herald, 2013). This accident reflected the representative example of the second composite disaster caused by the first natural disaster such as heavy rainfall and storm surge. It was reported that steel mill industries were needed to establish a disaster response system as well as safety standard/guideline and education system to prevent such composite disasters. Several researchers on industrial disaster had been conducted without consideration of the connectivity between natural and industrial disasters. In other words, those researches had been conducted by separating the natural disaster and the industrial disaster. Previously, *Stephane et al.* (2010) calculated the amount of direct loss in terms of flooding size caused by storm surge and investigated sea-level rise for Copenhagen, Denmark(Hallegatte, 2012). *Robert et al.* (2001) studied an effective mitigation plan in terms of the damage caused by the storm surge with aspects of structure and non-structure(Burrus, Dumas, and Graham, 2000). *Paul et al.* (2008) estimated the flooding area of Boston, the U.S(Kirshen, Knee, and Ruth, 2008). In South Korea, Suh*et al.* (2015) estimated the height of the tsunami for the West Seaport area by comparing the symmetry and asymmetry of the typhoon wind field using the ADCIRC model(Suh, Lee, Kim, and Fleming, 2015).

Also, *Kang et al.* (2012) studied the pattern of Tsunami propagation for Gyeongnam state, South Korea(Kang, Moon, Nam, and Shim, 2010). *Park et al.* (2009) discussed the seawater flow model of MIKE21 by applying the monthly flow calculation method and they also studied the expected flooding area for Masan Bay, South Korea, through the flow model(Hong, Park, and Cho, 2008). It was pointed out that those researches had limitations in addressing modern composite disasters caused by a natural disaster, which were becoming more complex and diverse in current industrial fields. It was also emphasized that the research should be conducted by choosing certain industry considering its specific work process and its environment in terms of the composite disaster. As it is mentioned above, for the reason of that the steel mill industries are generally located near thecoast, the research on the composite disaster is emphasized to prevent the main issues of the vapor explosion caused by the first natural disaster (*e.g.*, heavy rainfall and storm surge). Again, from the literature review, it was analyzed that those previous researches conducted on the natural disaster, were needed to be considered the second composite disaster. Therefore, this research was aimed to analyze the areas which could be under a risk of vapor explosion caused by storm surge for certain major steel mill company POSCO in South Korea. Notably, it was mentioned that the study considered the continuous disaster (from natural to industrial disaster) by performing the tide level frequency analysis and consequence by using program Coastal adaptation to sea-level rise (COAST) to simulate and estimate the flooding impact.

II. HEADINGS

Methods: The methodology in this research paper includes the implementation of risk assessment to show risk of storm surge in terms of steel mill industry which is typically located adjacent to sea. As a basic approach, the fundamentals of vapor explosion theory were introduced and finally derived appropriate mitigation plans to prevent and protect the steel mill industries by adapting the concept of the risk assessment.

Vapor Explosion: Vapor explosion, may could take place in steel mill industries, is a physical phenomenon that occurs when high-temperature molten metal contacts water. It causes extreme boiling by rapid heat transfer from molten metal to moisture in the storage vessel or on the bottom of the dry pit, as shown in the **Figure 2**. The procedure of the vapor explosion is addressed as three steps as: 1. Triggering phase (destruction of vapor film due to external pulse or instability), 2. Propagation phase (pressure wave transfer by rapid vaporization of water) and 3. Expansion phase (boiling by extreme reaction of molten metal and water) (Takashima and Iida 1995). The risk of the vapor explosion of steel mill industries can be increased when the environment of the working places is under wet conditions due to heavy rain or storm surge. For the reason that the high-temperature molten metal is transported through the diverse routes, it increases the chance to contact the molten metal and water.

Tide Frequency Analysis: The frequency analysis was performed by following the procedure as shown in the **Figure 3** below. In this study, Frequency Analysis of Rainfall Data (FARD) program was used to conduct the frequency analysis to estimate flooding area caused by storm surge to predict the frequency of high tide level (Shin, Kim, and Heo, 2007).

Data Collected and Preliminary Statistical Analysis: The statistical data of hourly tide level for past 43 years reported by Korea Hydrographic and Oceanographic Agency (KHOA) was collected to conduct the frequency analysis. 10 numbers of rainfall duration were sorted out from the statistical data based on the basic statistics analysis by considering the skewness and kurtosis coefficients and they were tabulated in **Table 1.** Before using the statistical data collected, it was analyzed that the preliminary review test was conducted to confirm its randomness and overall trend of the aggregated statistical data by four tests such as Anderson Correlogram Test(Anderson, 1994), Run Test(Bradley, 1968), Spearman Rank Correlation Coefficient Test(Rovai, Baker, and Ponton, 2013), and Turning Point Test(Stallings, 1995). In Anderson Correlogram (Equations 1.1, 1.2 and 1.3), the autocorrelation coefficient with respect to the samples has normal distribution with the number of 0 as mean value and with the $\frac{1}{N}$ of the variance in accordance with the sample size of N increases.

(Equation 1.1, 1.2, 1.3)

Where, γ_k is the autocorrelation coefficient, N is the sample size, Var is the variance, $v_{1-\alpha/2}$ is the quantile with respect to $1-\alpha/2$ and α is the level of significance. In the run test, total number of the run, the variance and the test statistic can be expressed as Equation 2.1, 2.2 and 2.3.

(Equation 2.1, 2.2, 2.3)

Where, N_1 is the number of 1(s) and N_2 is the number of 0(s). When the random variable is less than the quantile $\left(|U_c| \leq U_{1-\alpha/2}\right)$, it can be confirmed that there is randomness where α is the level of significance. The Equation 3.1 and the Equation 3.2 are to be found in Rank Correlation Coefficient Test.

(Equation 3.1, 3.2)

Where,R is the rank correlation coefficient, $i - \omega_i$ is the difference between the two ranks of each observation, N is the sample size and the T_c implies the Student's t-distribution with $N - 2$ degree of freedom under the null hypothesis. Equation 4.1, 4.2 and 4.3 were described as the procedure of Turning Point Test:

(Equation 4.1, 4.2, 4.3)

Turning point test is the test for randomness which can determine if the peaks and the turning points of a serial data is independent of the order of the observations. The Equation 4.1 is for estimating the number of the turning points which is calculated by the number of the samples in the data where N is the number of samples in the data. The Equation 4.2 is referred as Variance and the Equation 4.3 is the final procedure to estimate the z-value. As a result shown in the **Figure 3**, Anderson Correlogram Method approved that there was no randomness, Run Test showed that there was no randomness except 48 hours data, and no randomness was found as a result of Spearman Rank Correlation Coefficient Test except 1 hr, 2 hr and 24 hr data. In case of Turning Point Test, every data showed randomness. It was confirmed that the results from those four preliminary tests for the statistical data from KHOA were applicable in this study, as shown in the **Table 2** and the **Table 3**.

Estimate Parameters: Gumbel distribution(Gumbel, 1954) and method of probability-weighted moments(Greenwood, Landwehr, Matalas, and Wallis, 1979) were used to find out the parameters based on the probabilistic distribution. It is known that the Gumbel distribution is useful to estimate unbiased values by making up the limitation of using the method of moments since the method of moments estimates incomplete values in case of the skewed distribution.
The Gumbel distribution was expressed as the Equation 5:

(Equation 5)

where, α is the scale parameter and x_0 is the location parameter.
The method of probability-weighted moments was applied as shown in the Equation 6.

(Equation 6)

Where, p, r and s are the real numbers (*e.g.*, if $r = s = 0$ and p is the nonnegative integer, then $M(p, r, s)$ represents the conventional moment about the origin of order. Parameters were estimated as shown in the **Table 4**, and it was confirmed whether the Gumbel distribution could be applied or not by validation check.

Validation of the Parameters: After check if the estimated parameters were applicable to Gumbel distribution as shown in the **Table 4**, it was needed to be validated if the parameters were applicable to frequency analysis or not by using relative frequency function and cumulative frequency function with respect to theoretical values and sample values. Four methods were used to validate the parameters such as X^2 Test (Equation 7.1)(McHugh, 2013), Kolmogorov Smirnov Test (Equation 7.2)(Kolmogorov, 1933), Cramer Von Mises Test (Equation 7.3)(Cramér, 1928a, 1928b) and Probability Plot Correlation Coefficient (PPCC) Test (Equation 7.4)(Filliben, 1975).

(Equation 7.1, 7.2, 7.3, 7.4)

The X^2 test is known as the most useful statistics for testing hypotheses when the variables are nominal where e_i is the expected value, n_i is the actual count of cases in each cell of the table and q is the Chi-square value. Different from X^2 test, Kolmogorov Smirnov Test is using the Cumulative Distribution Function (CDF) instead of Probability Density Function (PDF). It is defined by a maximum deviation from comparison between the cumulative distribution for a sample and the distribution by hypotheses. As shown in Equation 7.3, Cramer Von Mises is the test for testing the distributed random variables with given continuous distribution where W is the numerical value referred to omega-squared distribution, F_X is the empirical distribution function and the N is the number of samples. Probability Plot Correlation Coefficient Test is the graphical technique for estimating the shape parameter. The location parameter and the scale parameter are to be shown in the Equation 7.4. The validated parameters based on Gumbel distribution were confirmed that they were applicable to frequency analysis by four test methods, as shown in the **Table 5**.

Frequency Analysis of Tide Level in Various Period: Based on the statistical data of hourly tide level for past 43 years (1972 – 2014) reported by Korea Hydrographic and Oceanographic Agency (KHOA), it was confirmed that the data was applicable to this research by sorting out the data with respect to 10 rainfall duration through fundamental statistics analysis considering the skewness and kurtosis coefficients. In addition, four preliminary tests were conducted to check if the sorted data could be applicable or not. After that, Method of Probability Weighted Moments was used to estimate parameters by applying Gumbel distribution. It was also validated that obtained parameters were relevant to be used as frequency for risk assessment for the reason of that the risk is defined as the product of frequency and consequence. The tide level in terms of Gumbel distribution was tabulated with respect to frequency, as shown in the **Table 6.** It was noted that the Gumbel distribution parameters from the year of 1972 to 2007 were confirmed as 55.9 and 12.1 for position and scale parameter by Jeong *et al.* (2008)(Jeong, Kim, Ko, and Yoon, 2008). The tide level by frequency in various periods (10 years, 20 years, 30 years, 50 years, 200 years) based on Gumbel distribution was estimated and tabulated as shown in the **Table 7**. By comparison with data discussed in this paper, it was identified that the result showed a difference about 1.72 ~ 2.17 cm as the current study added more statistical data from the year of 2008 to 2014**.**

COAST Simulation: Storm Surge Impact Analysis: COAST (coastal adaptation to sea-level rise tool) is an assessment tool to provide information of property damage based on scenarios through one-dimensional analysis of flooded areas due to sea-level rise with obtained database of geographical information and asset information (Kirshen *et al.*, 2008). In order to mitigate the risk in terms of natural disasters for industries that are located near the coastal area, it is important to identify risk areas in advance. In this study, COAST was used to seize the risk areas of POSCO by following the procedure as shown in the **Figure 4**. For the reason that the study was not aimed to estimate the amount of flood damage (cost), two input values such as depth damage function and adaption were to be negligible. The simulation model was designated by considering actual field measurements so that the model took account the rise of tide level by frequency and the rate of sea-level rise per year.

Digital Elevation Model (DEM) and Vector: By using numerical map information, the subject area of POSCO located in Pohang city, South Korea, was described to analyze flooding area caused by storm surge, as shown in the **Figure 5**.1:5,000 of scale and GRS80 (TM Eastern) of coordinate were used. The altitude of the terrain was designated by using Triangulated Irregular Network (TIN) based on the interpolation of contour and elevation and combination of the layers. In addition, each value for local sea level rise was tabulated in **Table 8.** It was noted that the difference between the sea level and the ground was very variable due to the operation of the ship at the point A, B and C. Therefore, the reference local sea level rise was measured in the absence of ship operation and applied in this study. The arithmetic means value of 0.5 m was determined as the base water level by measuring the difference between sea level and ground level of 10 main areas (a-j) in POSCO as shown in the **Figure 6**.

Input Parameters for COAST Simulation: The probability of the storm surge event was estimated by applying the exceedance curve. It was necessary that the recurrence interval[1], probability[2] and surge height were to be defined to develop the exceedance curve in the program, as shown in the **Table 9**.

Risk Assessment: To estimate risk areas in POSCO with respect to the vapor explosion, it was needed to investigate the locations for transporting and carrying high-temperature molten metal because the vapor explosion occurs when high-temperature molten metal contacts with water.

Locations for Transporting and Carrying High-Temperature Molten Metal in POSCO: As shown in **Figure 8**, it was investigated that POSCO had more than 100 equipment (100 tons and 320 tons) for transporting high-temperature molten metal and 90 km long track. The equipment was operated by remote operation via portable transmitter or by operators' direct operation.

III. RESULTS

The risk areas in terms of the vapor explosion were analyzed based on the results of storm surge flood analysis by considering the investigated location that carried the high-temperature metal. The levels of the frequency and the consequence were tabulated in **Table 11** and **Table 12**. It was noted that the 1 location was flooding in case of the flooding area up to 1,700 m^2 and the 2 locations were in the scope of flooding area between 1,700 m^2 and 3500 m^2. As shown in the **Figure 9**, the risk matrix was developed based on the levels of frequency and consequence as shown in the **Table 12** and the **Table 13**. The risk was evaluated based on its definition that the risk is a product of frequency and consequence. It was noted that the level of risk was defined as; Low (1-2), Moderate (3-4), High (5-8) and Very High (9-16). The result was tabulated in **Table 13** based on the result of the simulation in **Figure 10**.

1 Recurrence Interval: Repeated interval of one occurrence of storm prediction

2 Probability: Possibility of a storm surge in a year (must match the recurrence interval)

IV. DISCUSSION

Flooding was started in 2016 with a frequency of 10 years when the height of storm surge was 1.42 m corresponding flooding area of 1,568 m^2. In addition, from 2016 with the frequency of 50 years to 2026 with the frequency of 200 years, the flooding area was estimated as 1,689 m^2 and the height of the storm surge was found as between 1.6 and 1.9 m. In the period, the flooding area was not in the range of the location for transporting the high-temperature molten metal but for processing to treat product after steelworks so that there was no risk of vapor explosion. In addition, the flooding area was expanded to 2 locations between the year of 2036 with the frequency of 100 years and 2046 with the frequency of 200 years, which recorded the height of the storm surge as 1.97 m. However, for the reason that the locations were used as storage treating products from ships, it was investigated that there was no risk of the vapor explosion. From the year of 2056 with frequency of 50 years, it was confirmed that the flooding area was in the scope of the location for treating high-temperature molten metal. Especially, as the height of storm surge increased to 2.56 m, the flooding area was expanded extremely as 33,693 m^3 and the corresponding level of the risk on the vapor explosion increased rapidly. It was noted that, although risk of the vapor explosion was not found in the period from 2016 to 2046, flooding by storm surge event may accompany diverse kinds of composite disaster such as vapor explosion. Therefore, the risk was evaluated as well.

INDENTATIONS AND EQUATIONS

$$\mathrm{E}(\gamma_1) = -\frac{1}{(N-1)}$$ Equation 1.1

$$\mathrm{Var}(\gamma_1) = \frac{(N-2)}{(N-1)^2}$$ Equation 1.2

$$\left[\frac{-v_{1-\alpha/2}}{\sqrt{N}}, \frac{v_{1-\alpha/2}}{\sqrt{N}}\right]$$ Equation 1.3

$$\mathrm{E}(U) = \frac{2N_1N_2}{N_1+N_2} + 1$$ Equation 2.1

$$Var(U) = \frac{2N_1N_2(2N_1N_2 - N_1 - N_2)}{(N_1+N_2)^2(N_1+N_2-1)}$$ Equation 2.2

$$U_c = \frac{U - E(U)}{\sqrt{Var(U)}}$$ Equation 2.3

$$\mathrm{R} = 1 - \frac{6\sum_{i=1}^{N}(i-\omega_i)^2}{N(N^2-1)}$$ Equation 3.1

$$T_c = \frac{R\sqrt{N-2}}{\sqrt{1-R^2}}$$ Equation 3.2

$$\mathrm{E}(M) = \frac{2(N-2)}{3}$$ Equation 4.1

$$Var(M) = \frac{(16N-29)}{90}$$ Equation 4.2

$$U_c = \frac{M - E(M)}{\sqrt{V_{ar}(M)}}$$ Equation 4.3

$$f(x) = exp\left\{-exp\left[-\frac{(x-x_0)}{\alpha}\right]\right\}$$ Equation 5

$$M(p,r,s) = E[X^p\{F(X)\}^r\{1-F(X)\}^s]$$ Equation 6

X^2 Test: $$q = \sum_{i=1}^{m}\frac{(n_i-e_i)^2}{e_i}$$ Equation 7.1

Kolmogorov Smirnov: $$q = \text{Max}\left|\hat{F}_r(x) - F_0(x)\right|$$ Equation 7.2

Cramer Von Mises: $$W = \frac{1}{12N} + \sum_{i=1}^{N}\left[F_X(x_i;\hat{\theta}) - \frac{2i-1}{2N}\right]^2$$ Equation 7.3

PPCC: $$r_c = \frac{\sum_{i=1}^{N}(X_i-\bar{X})(M_i-\bar{M})}{\sqrt{\sum_{i=1}^{N}(X_i-\bar{X})^2\sum_{i=1}^{N}(M_i-\bar{M})^2}}$$ Equation 7.4

FIGURES AND TABLES

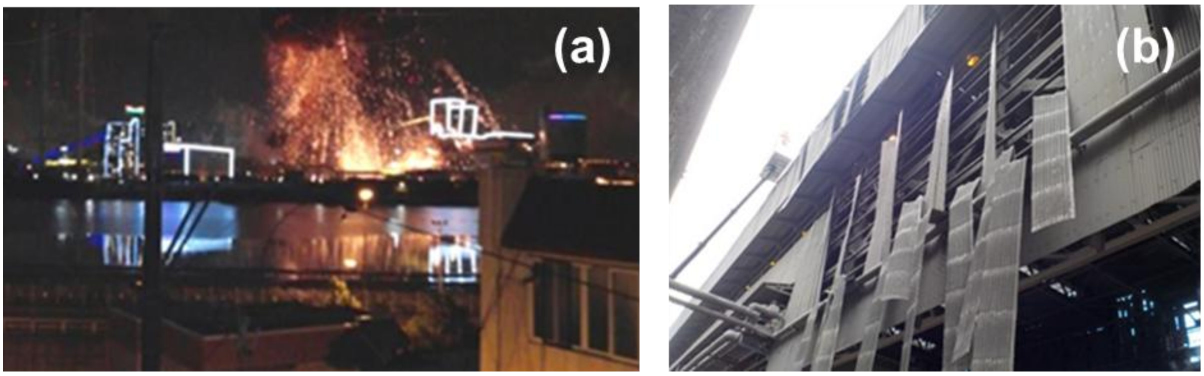

Fig. 1 (a) Vapor explosion occurred due to heavy rain period, July 2013, Pohang, South Korea **(b)** Second composite disaster caused by the accident occurred on July 2013, Pohang, South Korea

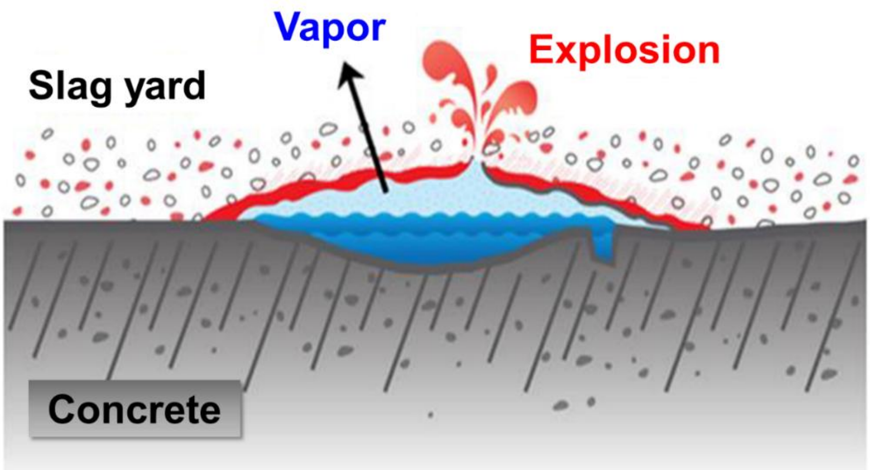

Fig. 2 Fundamentals of Vapor explosion, Water contacts with high-temperature molten slag on concrete layer

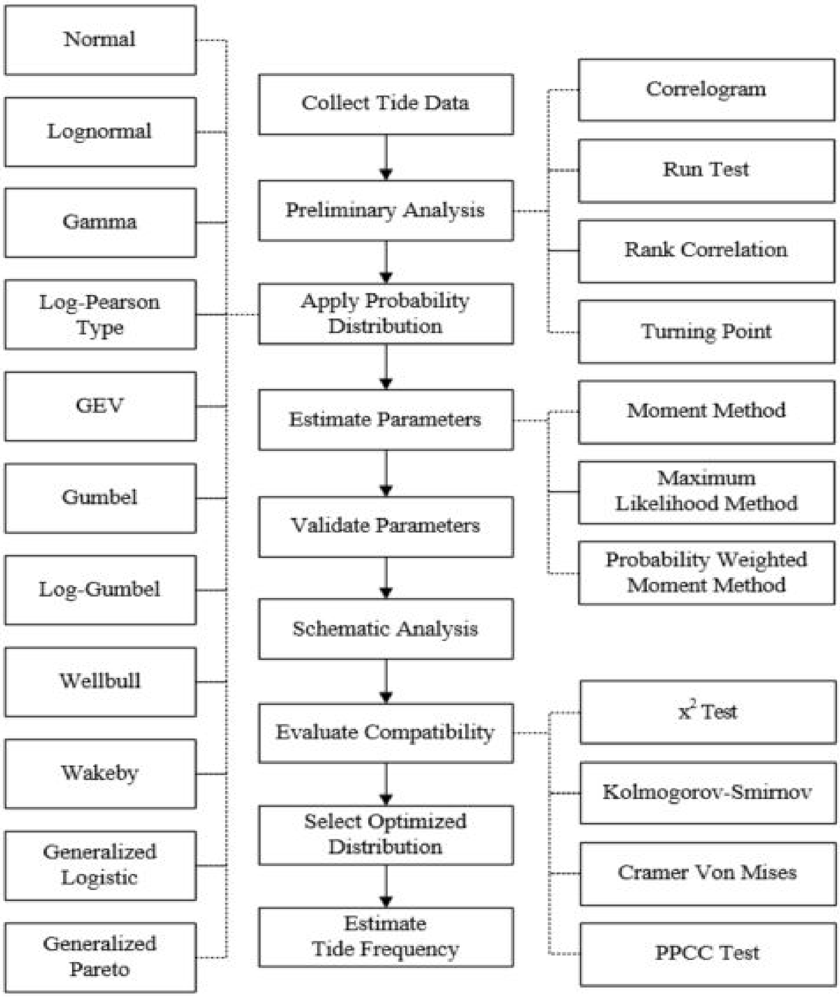

Fig. 3 Frequency analysis process, implemented functions, test methods and theory

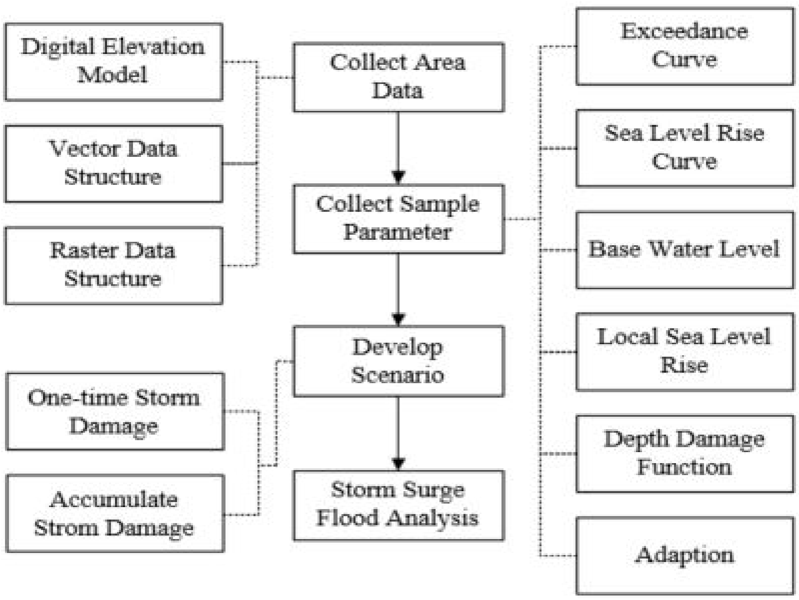

Fig. 4 Process to run COAST simulation program

Fig. 5 Study site in Pohang city, Gyeongsangbuk-do, Republic of Korea (POSCO)

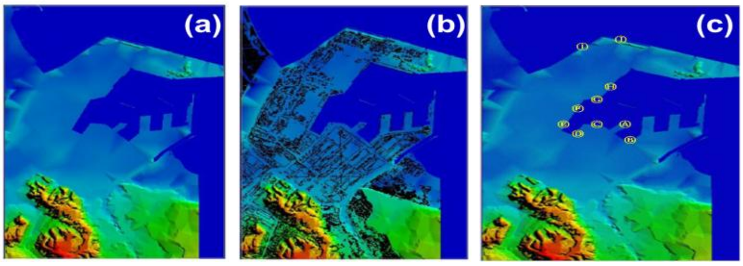

Fig. 6 (a) Digital Elevation Model, (b) Vector Structure and (c) Locations for field surveying of base water level

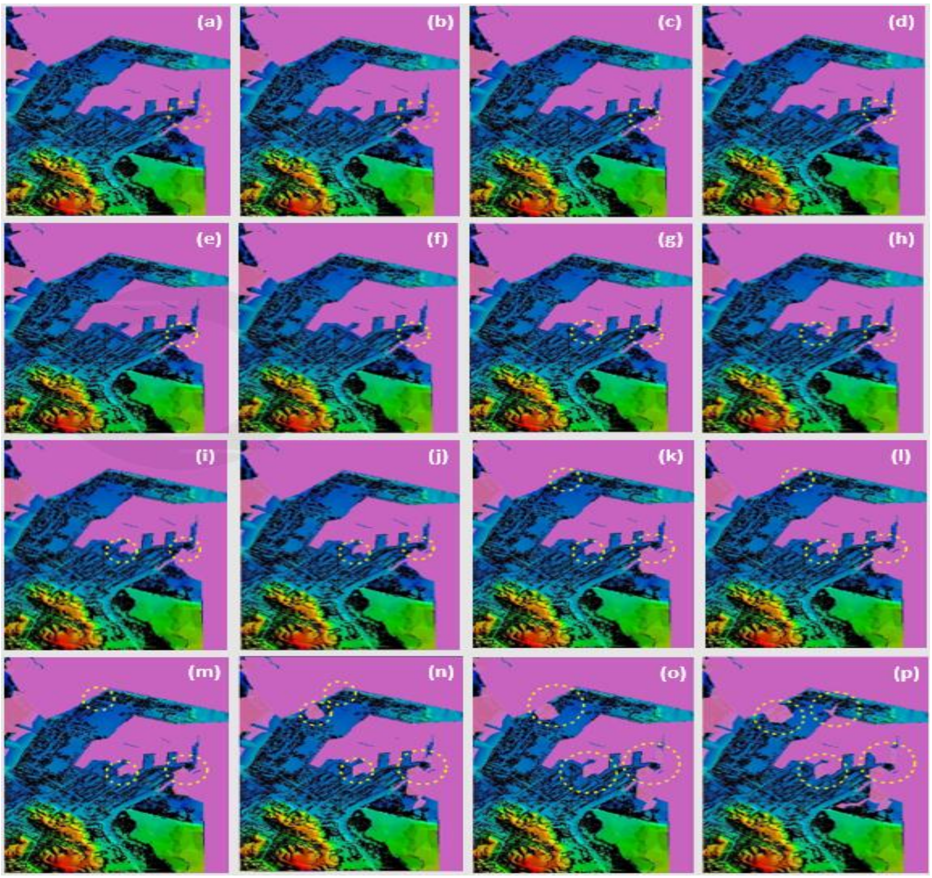

Fig. 7 Simulation result for 16 number of storm surge events by considering sea-level rise (Reflects the red marks in the Table 10)

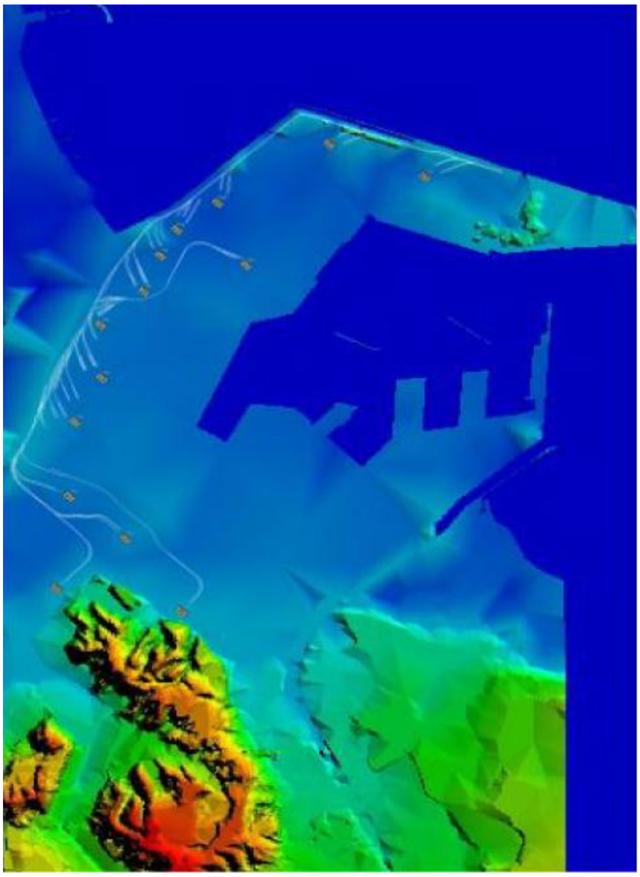

Fig. 8 Locations for transporting and carrying high-temperature molten metal in POSCO to estimate direct risk of vapor explosion on the study cite

		Consequence			
		1	2	3	4
Frequency	1	1	2	3	4
	2	2	4	6	8
	3	3	6	9	12
	4	4	8	12	16

Very High
High
Moderate
Low

Figure 9 Developed risk matrix to show more quantitatively risk of the vapor explosion by considering frequency and consequence

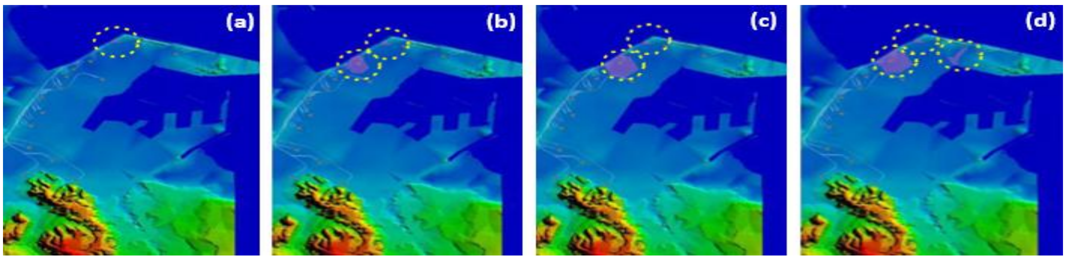

Fig. 10 (a) In 2056 with frequency of 50-200 years, (b) In 2066 with frequency of 50 year, (c) In 2066 with frequency of 100 year, (d) In 2066 with frequency of 200 year

Table 1. *Data sorted from KHOA*

Rainfall Duration [hr]	Mean Value [mm]	Standard Deviation	Variation Coefficient	Skewness Coefficient	Kurtosis Coefficient
1	66.3	12.5	0.219	0.386	3.065
2	131.9	28.3	0.215	0.289	2.813
3	196.3	41.3	0.210	0.246	2.784
6	382.2	76.2	0.199	0.097	2.634
9	558.5	110.2	0.197	0.132	2.786
12	730.0	143.1	0.196	0.151	2.899
15	895.9	176.4	0.197	0.163	2.911
18	1054.0	208.5	0.198	0.187	2.837
24	1353.1	272.9	0.202	0.178	2.765
48	2545.5	492.1	0.193	0.112	2.741

Table 2. *Comparison of calculated randomness coefficients results*

Rainfall Duration [hr]	ACM[3]		RT[4]		SRCCT[5]		TPT[6]	
	Calculated	Table	Calculated	Table	Calculated	Table	Calculated	Table
1	1.000	0.500	2.605	1.960	1.977	2.020	0.493	1.960
2	1.000	0.500	2.622	1.960	1.981	2.020	0.493	1.960
3	1.000	0.500	2.622	1.960	2.045	2.020	0.493	1.960
6	2.000	0.500	2.605	1.960	2.098	2.020	0.246	1.960
9	2.000	0.500	2.605	1.960	2.123	2.020	0.616	1.960
12	2.000	0.500	2.931	1.960	2.196	2.020	0.616	1.960
15	2.000	0.500	2.931	1.960	2.130	2.020	0.616	1.960
18	2.000	0.500	2.931	1.960	2.147	2.020	0.246	1.960
24	2.000	0.500	2.294	1.960	1.984	2.020	0.616	1.960
48	2.000	0.500	1.631	1.960	2.198	2.020	0.616	1.960

Table 3. *Validity check for randomness test results*

Rainfall Duration [hr]	ACM	RT	SRCCT	TPT
1	-	-	O	O
2	-	-	O	O
3	-	-	-	O
6	-	-	-	O
9	-	-	-	O
12	-	-	-	O
15	-	-	-	O
18	-	-	-	O
24	-	-	O	O
48	-	O	-	O

Table 4. *Estimated parameters and validation check for Gumbel distribution*

Rainfall Duration [hr]	Location	XMIN Observed	XMax Observed	Scale	Shape	Validity Check
1	59.373	37.0	105.0	11.965	0.000	O
2	118.360	74.0	202.5	23.430	0.000	O
3	176.527	111.0	297.0	34.181	0.000	O
6	345.592	217.0	541.0	63.399	0.000	O
9	505.926	314.0	776.0	91.145	0.000	O
2	661.919	401.0	1011.0	117.991	0.000	O
15	811.935	485.0	1256.0	145.401	0.000	O
18	954.705	583.0	1491.0	171.989	0.000	O
24	1222.856	757.0	1909.0	225.596	0.000	O
48	2310.445	1458.0	3622.0	407.214	0.000	O

[3] ACM: Anderson Correlogram Method
[4] RT: Run Test
[5] SRCCT: Spearman Rank Correlation Coefficient Test
[6] TPT: Turning Point Test

Table 5. *Four validation methods of parameters in Gumbel distribution*

Rainfall Duration [hr]	X^2		KS[7]		CVM[8]		PPCC[9]	
	Calculated	Table	Calculated	Table	Calculated	Table	Calculated	Table
1	4.58	7.81	0.08	0.18	0.06	0.46	0.99	0.96
2	3.19	7.81	0.08	0.18	0.06	0.46	0.98	0.96
3	2.01	7.81	0.07	0.18	0.06	0.46	0.98	0.96
6	2.01	7.81	0.09	0.18	0.08	0.46	0.97	0.96
9	2.63	7.81	0.10	0.18	0.09	0.46	0.97	0.96
12	2.01	7.81	0.09	0.18	0.07	0.46	0.97	0.96
15	2.91	7.81	0.08	0.18	0.06	0.46	0.97	0.96
18	1.23	7.81	0.09	0.18	0.07	0.46	0.98	0.96
24	0.40	7.81	0.10	0.18	0.08	0.46	0.98	0.96
48	3.47	7.81	0.12	0.18	0.12	0.46	0.98	0.96

Table 6. *Tide level by frequency in various periods*

Frequency [Year]	Tide Level [cm]
2	63.8
3	70.2
5	77.3
10	86.3
20	94.9
30	99.9
50	106.1
70	110.1
80	111.7
100	114.4
150	119.3
200	122.7
300	127.6
500	133.7

Table 7. *Comparison of estimated tide levels [cm]*

	Frequency [years]	10	20	30	50	100	200	500
Tide Level [cm]	Current Study	86.3	94.9	99.9	106.1	114.4	122.7	133.7
	Jeong *et al.* (2008)	84.13	92.84	97.85	104.11	112.56	120.98	-
	Difference	2.17	2.06	2.05	1.99	1.84	1.72	-

[7] KS: Kolmogorov Smirnov Test
[8] CVM: Cramer Von Mises Test
[9] PPCC: Probability Plot Correlation Coefficient

Table 8. *Summary of base water level for COAST simulation [m]*

Location	Land Elevation	Depth to Sea Surface	Base Water Level
A	3.30	2.45	0.85
B	3.59	2.65	0.94
C	3.43	3.10	0.33
D	3.73	2.80	0.93
E	3.56	3.15	0.41
F	3.60	3.30	0.30
G	3.49	3.20	0.29
H	5.06	4.80	0.26
I	4.41	4.10	0.31
J	3.58	3.20	0.38
Average base water level (Standard) [m]			0.5

Table 9. *Probability of storm event and height of storm surge*

Recurrence Interval [year]	**Probability**	**Height of Storm Surge [m]**
500	0.002	1.3
200	0.005	1.23
100	0.01	1.14
50	0.02	1.06
20	0.05	0.95
10	0.1	0.86

Table 10. *Storm surge event value by considering sea-level rise [m]*

Frequency [years] / Year	10	50	100	200
2016	**1.42 (a)**	**1.60 (b)**	**1.68 (c)**	**1.77 (d)**
2026	1.53	1.73	**1.81(e)**	**1.90 (f)**
2036	1.68	1.89	**1.97 (g)**	**2.06 (h)**
2046	1.86	2.06	**2.14 (i)**	**2.23 (j)**
2056	2.09	**2.30 (k)**	**2.37 (l)**	**2.46 (m)**
2066	2.36	**2.56 (n)**	**2.63 (o)**	**2.73 (p)**

Table 11. *Level of frequency to evaluate risk*

Classification	Level	Description
Possible	1	Occur once every 200 years
Very Possible	2	Occur once every 100 years
Probable	3	Occur once every 50 years
Very Probable	4	Occur once every 10 years

Table 12. *Level of consequence to evaluate risk*

Classification	Level	Description
Moderate	1	Flooding area up to 1,700 m^2 with no risk of vapor explosion
Significant	2	Flooding area more than 1,700 m^2 less than 3,500 m^2 with no risk of vapor explosion
Severe	3	Flooding area more than 3,500 m^2 less than 30,000 m^2 with risk of vapor explosion
Very Severe	4	Flooding area more than 30,000 m^2 with risk of vapor explosion

Table 13. *Risk Level by frequency and storm surge event value*

Year	Frequency [years]	Storm surge event value [m]	Flooding Area [m^2]	Level of Risk
2016	10	1.42	1,568.32	Moderate
	50	1.60	1,689.27	Moderate
	100	1.68	1,689.27	Low
	200	1.77	1,689.27	Low
2026	100	1.81	1,689.27	Low
	200	1.90	1,689.27	Low
2036	100	1.97	1,947.90	Moderate
	200	2.06	2,073.11	Low
2046	100	2.14	3,107.59	Moderate
	200	2.23	3,480.61	Low
2056	50	2.30	3,719.14	High
	100	2.37	3,802.36	High
	200	2.46	4,018.79	Moderate
2066	50	2.56	33,693.28	Very High
	100	2.63	47,712.65	Moderate
	200	2.73	62,733.19	Low

V. CONCLUSION

Risk assessment was performed on the representative steel mill company POSCO in South Korea to predict the composite disaster (*e.g.*, vapor explosion) caused by the natural disaster such as storm surge. The tide frequency analysis was performed based on the statistical data of hourly tide level for the past 43 years (1972 – 2014) reported by Korea Hydrographic and Oceanographic Agency (KHOA). It was investigated that the frequency of tide value was higher approximately 1.72 cm – 2.17 cm than the previous study for the reason of that the current research was including more statistical data from 2008 to 2014. By considering the rate of sea-level rise, storm surge event value was applied to the estimated frequency of the tide value to confirm the continuous safety for POSCO. In addition, it was investigated that some areas in POSCO started to be flooding from the year of 2016 with the frequency of 10 years. Flooding occurred at the local locations when the storm surge event values such as the year of 2016 with the frequency of 50 years, 100 years and 200 years or the year of 2026 with the frequency of 100 years and 200 years. It was also confirmed that more than 2 areas were flooding from the year of 2036 with the frequency of 100 years. In the year of 2046 with the frequency of 100 years and 200 years, the flooding area was started to be expand. It was investigated that the locations for transporting and carrying the high-temperature molten metal were under the flooding areas from the year of 2066 with frequency of 50 years, 100 years and 200 years so that the risk on the vapor explosion was investigated. Based on theresults, it was notable that POSCO was needed to be prepared to the composite disaster such as the vapor explosion by considering that the sea level is increasing. To prevent the vapor explosion, it is necessary to mitigate the triggering phase (destruction of vapor film due to external pulse of instability) which is one of the steps to occur the explosion by separating between high-temperature molten metal and moisture. As one of the economic mitigation plans for large scale steel mill industries such as POSCO, it was suggested that the locations for transporting and carrying the high-temperature molten metal should be isolated by operating the advance warning system. In addition, using overhead cranes could be another method to prevent the vapor explosion by raising the vessel containing the high-temperature molten metal from the areas subject to flooding by reducing the chance of contact the molten metal and water.

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