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Use of Non-Parametric Statistical Method in Identifying Repetitive High Dose Jobs in a Nuclear Power Plant

비모수통계방법을 이용한 원자력발전소 작업자 반복성 고피폭작업 도출

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Abstract

The cost-effective reduction of occupational radiation dose (ORD) at a nuclear power plant could not be achieved without going through an extensive analysis of accumulated ORD data of existing plants. Through the data analysis, it is required to identify what are the jobs of repetitive high ORD at the nuclear power plant. In this study, Percentile Rank Sum Method (PRSM) is proposed to identify repetitive high ORD jobs, which is based on non-parametric statistical theory. As a case study, the method is applied to ORD data of maintenance and repair jobs at Kori units 3 and 4 that are pressurized water reactors with 950 MWe capacity and have been operated since 1986 and 1987, respectively in Korea. The results was verified and validated, and PRSM has been demonstrated to be an efficient method of analyzing the data.

Key words : Occupational radiation dose, ALARA, Non-parametric statistical method

요약

원전 작업자 방사선량의 효과적인 저감을 위해서는 발전소 내에 축적된 작업자 피폭선량 자료들을 분석하는 것이 반드시 필요하다. 자료의 분석을 통해, 발전소에서 수행되는 방사선작업들 중 반복적으로 고피폭을 유발하는 작업들을 파악하는 것이 필요하며, 본 연구에서는 이러한 반복성고피폭작업들을 도출하기 위한 방법론으로 백분위수 순위합 방법을 제

안한다. 이는 비모수통계학 이론에 근거한 방법론으로, 본 연구에서는 이 방법을 이용하여 고리 3,4 호기 작업자 피폭선량 자료를 분석, 고피폭작업들을 도출하였다. 도출 결과는 통계적으로 검증되며, 그 결과 백분위수 순위합 방법의 효과 및 타당성을 입증하였다.

중심단어 : 작업자피폭선량, 합리적성취최저, 비모수통계방법

I. Introduction

Pursuant to the requirements of keeping occupational radiation dose (ORD) as low as reasonably achievable (ALARA), the effective reduction of ORD has always been one of the major concerns in the phases of design as well as operation of a nuclear power plant. It has been identified that a predominant portion of ORD arises during maintenance and repair period at nuclear power plants. For the cost-effective reduction of ORD, it is the first step to identify what are the jobs of repetitive high ORD during maintenance and repair period so that specified efforts could be focused to effectively reduce the ORD for ALARA implementation[1].

Each existing nuclear power plant in operation has been accumulating its own ORD data. Through a comprehensive analysis of the accumulated ORD data, it is possible to identify the jobs of repetitive high ORD during maintenance and repair period. The ORD data are composed of a set of collective dose data according to the each maintenance and repair job classification. In general, a mean or median value of the collective dose data is used in the analysis of the maintenance and repair jobs [2]. The point values, however, have crucial defects to be overlooked. The point values have no consideration for data distribution, that is, the total ORD data, so they are not appropriate to represent a maintenance and repair job. In this paper, Percentile Rank Sum Method (PRSM) is proposed to identify "repetitive" high ORD jobs more effectively, which is based on non-parametric statistical theory.

As a case study, PRSM is applied to ORD data of Kori units 3 and 4 that are pressurized water reactors with 950 MWe capacity and have been operated since 1986 and 1987, respectively in Korea.

II. Theory

Percentile Rank Sum Method (PRSM) is based on non-parametric statistical theory. A non-parametric procedure is a statistical procedure that has desirable properties that hold under underlying populations from which the data are obtained. Non-parametric methods require few assumption about the underlying populations from which the data are obtained. In particular, non-parametric procedures forgo the traditional assumption that the underlying populations are normal. Therefore, non-parametric procedures are applicable in situations in which the normal theory procedures cannot be utilized. For example, many of the procedures require not the actual magnitudes of the data, but rather, their ranks and signs [3]. In general, ORD data are categorized according to radiation job classifications. In some cases, the population of the categorized ORD data is not large enough to make a distribution or does not form a specific distribution. Therefore, non-parametric statistical method is preferable to parametric statistical method in the analysis.

The PRSM consists of four major steps: 1) characterization of radiation jobs; 2) derivation of percentile values for radiation job classifications; 3) identification of the repetitive high ORD jobs; and 4) verification and validation of the results.

The first step is to classify radiation jobs according to an existing radiation job classification structure. Without the existing structure, those widely used at other existing nuclear power plants could be referenced. The classification structure generally consists of main and detailed job codes each of which is broken down into as many details as are considered useful. And each maintenance and repair job is assigned to one of the radiation job classifications defined in the structure. As a result, for each radiation job classification, a set of collective dose data will be available. Then, a set of collective dose data will be compiled for each radiation job classification, which creates a distribution of collective dose data within the given radiation job classification.

The second step is to derive the percentile values of collective dose for each radiation job classifications. The collective dose data assigned to a given radiation job classification are sorted in order of increasing magnitude, which actually create a distribution function. For convenience of this study, 9 different distribution percentile values are chosen as follows: ξ = 10, 20, ..., 90 percentiles with 10 percentile increment. Table 1 shows how to derive the 9 percentile values from the total collective dose data of a radiation job classification. Example job is steam generator manway close job whose job code is B2.

In this case, for each of N radiation job classifications, 9 values of collective dose corresponding to 9 distribution percentiles are computed.

Let $\{S^j\}$ be a set of collective dose data for radiation job classification j in which the data, S^j_ξ are arranged in ascending order of collective dose as follows:

$$\{S^j\} = \{S^j_\xi \ ; \ S^j_{10} \leqq S^j_{20} \leqq \ldots \leqq S^j_{90}\} \quad (1)$$

where S^j_{10}, S^j_{20},... , S^j_{90} are the collective dose values of 10, 20,... , 90 percentiles of radiation job classification j respectively, and j = 1, 2, ... N.

The third step is to identify of the repetitive high ORD job. The collective dose data assigned to a given percentile value are sorted in order of increasing magnitude. Using matrix notation, collective dose data of all N radiation job classifications are arranged in all the 9 distribution percentiles as follows:

$$S = \begin{bmatrix} S^1_{10} & S^1_{20} & \cdots & S^1_{90} \\ S^2_{10} & S^2_{20} & \cdots & S^2_{90} \\ \vdots & \vdots & \ddots & \vdots \\ S^N_{10} & S^N_{20} & \cdots & S^N_{90} \end{bmatrix} \quad (2)$$

For a given distribution of percentile ξ, let's arrange the elements of column of Eq. (2) in ascending order of collective dose. Starting from 1, the rank assigned to the

Table1. Example for Deriving Percentile Values

Job Code & Title : B2 Steam Generator Manway Close Job			
Collective Dose (person-mrem)	Index	CDF	Percentile
D	i	F(Di) = i/(N+1)	
1	1	0.035	
1	2	0.069	
1	3	0.103	≒10th
51	4	0.138	
60	5	0.172	
93	6	0.207	≒20th
123	7	0.241	
128	8	0.276	
157	9	0.310	≒30th
247	10	0.345	
273	11	0.379	
365	12	0.414	≒40th
445	13	0.448	
524	14	0.482	
596	15	0.516	≒50th
717	16	0.552	
890	17	0.586	≒60th
909	18	0.621	
910	19	0.655	
975	20	0.690	≒70th
995	21	0.724	
1005	22	0.759	
1263	23	0.793	≒80th
1390	24	0.828	
1395	25	0.862	
1420	26	0.897	≒90th
1564	27	0.931	
3635	28	0.966	
	N=28		

matrix element (radiation job classification) with the smallest collective dose value fo distribution percentile ξ, the ranks of rest successively ascend one-by-one in order of increasing magnitude of collective dose. In addition, the ranks with the same collective dose are averaged.

Let R_ξ^j denote the rank of S_ξ^j. If we replace the elements of the matrix S_ξ^j with R_ξ^j, the rank matrix becomes

$$\mathbf{R}=\begin{bmatrix} R_{10}^1 & R_{20}^1 & \cdots & R_{90}^1 \\ R_{10}^2 & R_{20}^2 & \cdots & R_{90}^2 \\ \vdots & \vdots & \ddots & \vdots \\ R_{10}^N & R_{20}^N & \cdots & R_{90}^N \end{bmatrix} \qquad (3)$$

where R_ξ^j is within the range of [1, N].

Let $\sum R_\xi^j = \sum_\xi R_\xi^j$, which denotes the sum of ranks for radiation job classification j over all the 9 percentiles. Then, the rank sum matrix becomes

$$RS = \begin{bmatrix} R_{10}^{1} & R_{20}^{1} & \cdots & R_{90}^{1} & \sum R_{\xi}^{1} \\ R_{10}^{2} & R_{20}^{2} & \cdots & R_{90}^{2} & \sum R_{\xi}^{2} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ R_{10}^{N} & R_{20}^{N} & \cdots & R_{90}^{N} & \sum R_{\xi}^{N} \end{bmatrix} \quad (4)$$

Let the elements of the far right-hand side column in Eq. (4) be sorted in order of increasing magnitude, and let R_j be the rank of the rank sum of radiation job classification j. Then, repetitive high ORD jobs are identified using R_j. That is, the radiation job classification j with the larger value of R_j is considered as the one of higher ORD.

The fourth step is to verify and validate the results in the third step. If we replace $\sum R_{\xi}^{j}$ with R_j in Eq. (4), the verification and validation matrix becomes

$$VV = \begin{bmatrix} R_{10}^{1} & R_{20}^{1} & \cdots & R_{90}^{1} & R_{1} \\ R_{10}^{2} & R_{20}^{2} & \cdots & R_{90}^{2} & R_{2} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ R_{10}^{N} & R_{20}^{N} & \cdots & R_{90}^{N} & R_{N} \end{bmatrix} \quad (5)$$

It is required to check whether the rank of rank sum in Eq. (5)can represent each radiation jobclassification. It is also required to check whether the ranks drawn in the third step have the characteristics of homogeneity and represent the characteristics of a population. Wilcoxon signed rank test and Friedman test is used respectively [4]. Eq. (5) is used as the source file for the Wilcoxon signed rank test and Friedman test.

Ⅲ. Case Study

For a meaningful assessment of ORD, it requires at least 5 years or 4 effective full power years of operation for data collection [5]. Kori units 3 and 4 are selected for the case study. Kori units 3 and 4 are PWRs with 950 MWe capacity each and have been operating since 1986 and 1987, respectively. The ORD data used for the case study had been accumulated over a 10-year period from 1986 through 1995. The data are compiled into a PC-based ORD database program, INSTORE [6].

Table 2 summarizes the structure of radiation job classifications derived for a typical PWR nuclear power plant [7]. This structure has been adopted for the case study. There are 26 main job codes thatare further subdivided into detailed job codes. These job codes, all together constitute 74 radiation job classifications as shown in Table 2. Among the 74 radiation job classifications, 5 radiation job classifications (D1, D4, D8, F5, H6) were not performed at Kori units, and 7 radiation job classifications (C2, D6, P6, R0, T0, X0, Y0) had not sufficient data for a meaningful analysis. These 12 job classifications are excluded from the analysis. The remaining 62 job classifications are evaluated. A total of 4,335 collective dose data have been obtained. Each of them is assigned to one of 62 radiation job classifications.

Table 2. Radiation Job Classification

Main job code and title		Detailed job code and title
A	Reactor Job	A1 Preparatory Job, A2 Reactor Disassembling, A3 Fuel Withdrawal, A4 Fuel Inspection, A5 Fuel Loading, A6 Reactor Assembling, A7 Reactor Inspection, A8 Others
B	SG Manway Job	B1 Manway Open, B2 Manway Close, B3 Others
C	SG ECT Job	C1 Preparatory Job, C2 Inspection, C3 Template Construction & Removal, C4 Equipment Installation & Movement, C5 ECT, C6 Others
D	SG Tube Job	D1 Preparatory Job, D2 Inspection, D3 Template Construction & Removal, D4 Equipment Installation & Movement, D5 Plugging, D6 Sleeving, D7 Equipment Decontamination, D8 Others
E	SG Nozzle Dam Job	E1 Dam Construction, E2 Dam Removal, E3 Others
F	SG Lancing Job	F1 Preparatory Job, F2 H/H Job, F3 Lancing, F4 Equipment Removal & Decontamination F5 Others
G	SG Related Job	
H	RCP Check/Maintenance Job	H1 Preparatory Job, H2 RCP Motor Job, H3 RCP Seal & MFB Job, H4 RCP TVCS Job, H5 RCP DACS Replacement, H6 Others
I	PZR Check/Maintenance Job	
J	RHR Check/Maintenance Job	
K	In-Service Inspectio	K1 RT, K2 PT, K3 MT, K4 ET, K5 UT, K6 VT, K7 Others
L	Containment Leak Tes	
M	In-Core Job	M1 Thimble Job, M2 DFMS System Job, M3 Thermocouple Job, M4 Detector Jo
N	RTD Check/Maintenance Job	
O	Snubber Check/Maintenance job	
P	Valve Check/Maintenance job	P1 BB System, P2 BH System, P3 BG System, P4 BM System, P5 BC System, P6 HB System, P7 HC System, P8 Other
Q	P/P Check/Maintenance Jo	
R	Heat Exchanger j	
S	Filter J	
T	Evaporator J	
U	Decontamination/Laundry Job	
V	Waste Related Jo	
W	Radiation Safety Control	
X	System Operation	
Y	Waste Drum Deposit J	
Z	Others	

For each of 62 radiation job classifications, a set of 9 percentile dose values are computed based upon the assigned dose data.In this way, the collective dose matrix (9x62), S is formulated for rank sum analysis. Arranging the elements of a given column of matrix, S, in ascending order of magnitude of collective dose, the ranks are assigned starting from 1 for the smallest and successively ascend one-by-one. When the collective doses are same, the average value is used. The rank matrix, R, is assembled by replacing each element of S with the rank of the element. The next step is to compute the sum of ranks in each radiation job classification, and to rank the rank sums. Table 3 shows the ranks of each percentile value, rank sums, and ranks of rank sum for 62 radiation job classifications.

Top 20 repetitive high ORD jobs are identified and presented in Table 4. Since these jobs dominate the major portion (about 70 %) of collective dose, they should be closely scrutinized to derive the means of cost-effective ORD reduction in compliance with the requirements of ALARA. To demonstrate the advantage of Percentile Rank Sum Method over Point Dose Value Method (e. g. median), two example cases are specified in Table 5. In identifying "repetitive" high dose jobs, Percentile Rank Sum Method is proved to be more efficient method than Point Dose Value Method.

Verification and validation of the results is performed with Wilcoxon signed rank test and Friedman test using the test matrix in Eq. (5). Wilcoxon signed rank test is performed to check whether the rank of rank sum of radiation job classification j in Eq. (5), R_j, can represent the ranks of 9 percentile values of the radiation job classification j. The test is performed at significance level α = 0.05. The results of Wilcoxon signed rank test are presented in Table 6. W^+ in the table is test statistic, and $w^+(x,n)$ is the sum of the signed ranks that is equal to W^+. The results show that most radiation job classifications (58 jobs) have passed in the test except for 2 radiation job classifications (P5, V0). Radiation job classifications K4 and E1 had insufficient data, and radiation job classifications P5 and V0 failed to pass in the test. Friedman test is performed to check whether the ranks drawn in the third step have the characteristics of homogeneity and represent the characteristics of a population. The results of test show that test statistic S, is computed to be 7.1516. This value is compared with the value of $\chi^2_{(9,0.05)}$ whichis defined as the upper 0.05 percentile point of the χ^2 distribution with degree of freedom of 9. The comparison of two values shows that S is less than the value of $\chi^2_{(9,0.05)}$ (= 16.92), which means that 10 samples (9 percentile values plus 1 rank sum value) have the characteristics of good homogeneity and well describe the characteristics of a population. Through the tests, the results are accepted to be statistically significant.

Ⅳ. Conclusions

The effective reductionof ORD in a nuclear

Table 3. Summary of Radiation Job Classifications in Kori Units 3 & 4

Job code	Rank of each percentile									Rank sum	Rank of rank sum
	10%	20%	30%	40%	50%	60%	70%	80%	90%		
A1	5.5	25	24	24	31	30	33	32	31	235.5	28
A2	60	57	56	57	58	58	58	58	58	520	58
A3	42	30	26	22	22	15	19	22	21	219	26
A4	21	11.5	8	5	5	7	5	5	5	72.5	6
A5	23	20	13	9	9	5	8	9	12	108	9
A6	50	60	58	61	60	60	61	61	61	532	60
A7	39	35	32	34	29	31	32	30	30	292	34
A8	31	27	28	25	25	23	23	19	16	217	25
B1	44	42	37.5	38	40	40	45	45	44	375.5	42
B2	14	41	42	49	50	54	49	50	46	395	44
B3	5.5	23	33	36	36	36	39	36	39	283.5	33
C1	12	22	19	20	21	21	16	18	15	164	20
C3	43	45	39	41	45	39	38	37	36	363	41
C4	61	52	47	44	39	44	40	41	37	405	46
C5	53	51	52	53	51	52	52	52	51	467	53
C6	33	34	35	33	33	28	26	28	28	278	31
D2	27	16.5	10	7	6	4	4	4	4	82.5	7
D3	48	38	36	32	30	27	34	34	35	314	35
D5	59	46	50	43	57	50	48	44	52	449	51
D7	19	10	7	4	4	2	2	2	2	52	3.5
E1	58	62	62	62	62	62	62	62	62	554	62
E2	32	32	48	50	46	51	50	48	45	402	45
E3	41	28	23	19	14	33	28	23	17	226	27
F1	18	26	22	21	17	20	29	29	27	209	24
F2	56	49	44	45	41	43	46	46	48	418	47
F3	57	54	51	52	48	46	43	42	41	434	48
F4	30	19	17	12	11.5	11	12	11	11	134.5	15
G0	5.5	3.5	6	6	7	6	6	7	10	57	5
H1	54	53	53	54	56	55	53	55	54	487	56
H2	62	61	61	59	59	59	59	59	60	539	61
H3	47	56	57	56	53	53	55	54	53	484	54.5
H4	46	58	59	60	61	61	60	60	59	524	59
H5	17	59	60	58	52	48	54	51	50	449	51
I0	35	33	31	30	34	34	31	27	24	279	32
J0	5.5	3.5	18	16	15	14	21	20	23	136	16
K1	5.5	3.5	5	13	20	24	15	21	26	133	14
K2	45	55	55	55	54	57	56	56	55	488	57
K3	13	8	4	3	3	1	1	1	1	35	2
K4	5.5	3.5	1.5	1	1	3	3	3	3	24.5	1
K5	16	11.5	15	28	28	32	27	25	25	207.5	23
K6	20	16.5	16	15	23	16	17	15	14	152.5	17
K7	34	39	41	40	42	41	42	40	38	357	40
L0	22	13	21	17	13	12	11	12	8	129	13
M1	55	50	49	48	49	49	51	49	49	449	51
M2	49	44	40	39	37	37	35	35	34	350	39
M3	28	21	14	10	10	9	10	8	9	119	10
M4	40	31	27	29	27	26	25	26	22	253	29

Table 4. Top 20 Repetitive High ORD Jobs in Kori Units 3 and 4

Job code	Main job title	Detailed job title	Rank sum
E1	SG nozzle dam job	Dam construction	554
H2	RCP check & maintenance job	RCP motor job	539
A6	Reactor job	Reactor assembling	532
H4	RCP check & maintenance job	RCP TVCS job	524
A2	Reactor job	Reactor disassembling	520
K2	In-service inspection	PT	488
H1	RCP check & maintenance job	Preparatory job	487
P2	Valve check & maintenance job	BH system	484
H3	RCP check & maintenance job	RCP seal and MFB job	484
C5	SG ECT job	ECT	467
M1	In-core job	Thimble job	449
H5	RCP check & maintenance job	RCP DACS replacement	449
D5	SG tube job	Plugging	449
P1	Valve check & maintenance job	BB system	444
F3	SG lancing job	Lancing	434
F2	SG lancing job	H/H job	418
C4	SG ECT job	Equipment installation & movement	405
E2	SG nozzle dam job	Dam removal	402
B2	SG manway job	Manway close	395
P8	Valve check & maintenance job	Others	386

Table 5. Comparison of the results between PRSM and 50Percentile Method

(unit : person-mSv)

	Job Code	10%	20%	30%	40%	50%	60%	70%	80%	90%	Rank
Case I	A6	2.26	12.13	18.33	30.74	38.92	60.35	92.21	146.08	241.11	60
	H4	1.69	9.55	18.40	26.26	40.19	61.68	84.62	107.41	138.06	59
Case II	P1	2.60	5.20	7.80	11.70	15.60	23.40	31.20	53.30	108.68	49
	F3	3.96	6.99	9.37	14.52	16.90	20.66	23.50	31.42	39.20	48

Table 6. Results of Wilcoxon Signed Rank Test

Job code	W^+	$w^+(x,n)$	Remark	Job code	W^+	$w^+(x,n)$	Remark
A1	21	$W^+(0.500,9)$		H4	17.5	$w^+(0.344,7)$	
A2	3.5	$W^+(0.562,4)$		H5	21	$w^+(0.371,8)$	
A3	10.5	$W^+(0.527,8)$		I0	19	$w^+(0.500,9)$	
A4	27.5	$W^+(0.326,9)$		J0	17.5	$w^+(0.527,8)$	
A5	16.5	$W^+(0.156,6)$		K1	21.5	$w^+(0.500,9)$	
A6	10	$w^+(0.500,6)$		K2	0	$w^+(0.527,8)$	
A7	8.5	$w^+(0.527,8)$		K3	31	$w^+(0.180,9)$	
A8	11.5	$w^+(0.422,7)$		K4	28	$w^+(0.008,7)$	N/A
B1	19	$w^+(0.473,8)$		K5	23	$w^+(0.500,9)$	
B2	31.5	$w^+(0.180,9)$		K6	14.5	$w^+(0.527,8)$	
B3	21	$w^+(0.148,8)$		K7	14	$w^+(0.531,7)$	

Table 6. Results of Wilcoxon Signed Rank Test (계속)

Job code	W^+	$w^+(x,n)$	Remark	Job code	W^+	$w^+(x,n)$	Remark
C1	8.5	$w^+(0.527,8)$		L0	17	$w^+(0.344,7)$	
C3	14	$w^+(0.527,8)$		M1	8	$w^+(0.527,8)$	
C4	15.5	$w^+(0.500,9)$		M2	15	$w^+(0.527,8)$	
C5	0	$w^+(0.531,7)$		M3	15	$w^+(0.219,6)$	
C6	19.5	$w^+(0.500,9)$		M4	10	$w^+(0.527,8)$	
D2	19	$w^+(0.473,8)$		NO	23.5	$w^+(0.455,9)$	
D3	14.5	$w^+(0.527,8)$		O0	36	$w^+(0.064,9)$	
D5	16.5	$w^+(0.500,9)$		P1	23.5	$w^+(0.455,9)$	
D7	31	$w^+(0.180,9)$		P2	19.5	$w^+(0.500,9)$	
E1	0	n=1	N/A	P3	21.5	$w^+(0.148,7)$	
E2	21	$w^+(0.148,8)$		P4	17.5	$w^+(0.527,8)$	
E3	17	$w^+(0.500,9)$		P5	36	$w^+(0.004,8)$	failed
F1	18	$w^+(0.500,9)$		P7	39	$w^+(0.027,9)$	
F2	15.5	$w^+(0.500,9)$		P8	14	$w^+(0.531,7)$	
F3	18.5	$w^+(0.289,8)$		Q0	28	$w^+(0.285,9)$	
F4	12	$w^+(0.500,9)$		S0	19	$w^+(0.473,8)$	
G0	39	$w^+(0.027,9)$		U0	20.5	$w^+(0.500,9)$	
H1	0	$w^+(0.527,8)$		V0	34	$w^+(0.012,8)$	failed
H2	3	$w^+(0.531,7)$		W0	21	$w^+(0.148,8)$	
H3	19.5	$w^+(0.500,9)$		Z0	19	$w^+(0.500,9)$	

power plant could be achieved by analyzing existing ORD data, identifying repetitive high ORD jobs, and adopting effective means to reduce ORD, based upon the results of analysis. In general, the point values such as mean and median are used to identify the high ORD jobs. Since they cannot show other important characteristics such as dose distributions and frequencies of radiation jobs, however, the point value method sometimes leads to misjudgment. As an alternative, Percentile Rank Sum Method (PRSM) is proposed in this study, which is based on the non-parametric statistical theory. The method includes the verification and validation procedure for the results using Wilcoxon signed rank test and Friedman test. As a case study, it is actually applied to ORD database of Kori units 3 and 4, and is demonstrated to be a very efficient way of analyzing the ORD data.

V. References

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