A PROPOSED GUIDELINE FOR VERIFYING THE ATTAINMENT OF SOIL REMEDIATION FOR TAIWAN

Tsun-Kuo Chang*, Bai-You Cheng, and Guey-Shin Shyu

ABSTRACT

This paper proposes a technical guideline for evaluating the success of soil remediation efforts. Statistical methods have been emphasized because there is a practical need for decisions regarding whether a site has met a cleanup standard in spite of inherent uncertainty. Uncertainty arises because only small portions of the soil at the site can be sampled and analyzed while the decision for the entire site is solely based on the few samples available. To overcome this bias, statistical methods were designed to permit extrapolation of the results from a few samples in order to make a statement regarding the entire site. Our proposed guideline, being tested in four cases, can provide a technical interpretation of data analysis methods acceptable for verifying the attainment of a cleanup standard of soils media. The guideline includes four parameters: first, the concentration of every sample should be less than the control standard; second, the concentration of 97.5% probability of cumulative curve should not exceed the control standard; third, the median concentration of sampling should be below the monitoring standard; and fourth, the indicator of evenness for the remediation works should be less than two. In comparison with traditional methods, our proposed guideline is shown to be effective in verifying remediation results.

Key Words: soil pollution, remediation, verification method.

I. INTRODUCTION

Heavy metals are one of the serious pollutants in our natural environment due to their toxicity, persistence and bioaccumulation problems. While experiencing rapid industrial expansion, Taiwan has been suffering an ever-increasing impact from human activity. Some soil in agricultural fields has been so polluted by waste from industrial plants through irrigation systems that the pollution of farmland by heavy metals has become a subject of intense public concern. Moreover, in 2000, Taiwan's EPA also announced a "Soil And Groundwater Pollution Control Act" to tackle this serious problem. Under this Act, a nationwide investigation was carried out by EPA in 2002 to identify contaminated sites and suspected pollution sources of soil heavy metals. On the West side of Taiwan, some 252 hectares of farmlands were classified as control sites in the investigation. The remediation works have been underway to clean up the heavy metals and keep the soil safe to grow crops. The following steps must be taken in sequence to evaluate whether a site has attained the cleanup standard: (1) define the attainment objectives; (2) specify sample design and analysis plan, and determine sample size; (3) collect the data; and (4) determine if the sample area attains the cleanup standard. (U.S. EPA, 1989) In front of us is how to verify a successful cleanup of a remediated site in spite of inherent uncertainty, which arises because only small portions of the soil at the site can be sampled and analyzed while the decision for the entire site is based on the few samplings available. Consider the following scenario: the surface layer of soil from a 4-hectare farmland at a control site is sampled using the cores with a 4-cm area. Given the size of the core and farmland there would be approximately 10 million sample locations; however, metal concentration

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measurements would only be made on about 100 of the 10 million. Statistical sampling and analysis methods would be needed to provide an approach to choosing 100 out of the 10 million locations for sampling so that valid results could be attained and statements be made regarding the characteristics of the 10 million potential samples or the entire site. Obviously, variation in sampling and lab analysis could introduce uncertainty to the decision making for the attainment of a cleanup standard.

Traditional verification requires that a contaminated site be cleaned until the soil concentration of a chemical drops below the standards. (Wang, 1996; Chen, 2001) The soil pollution control standards are the prescribed measures with the purposes of preventing the aggravation of soil pollution under the "Soil and Groundwater Pollution Control Act". Allowing no exceeding of a standard is a perfectly acceptable decision rule to use. In fact, that simple rule is a statistical procedure because errors are possible. However, even there are no excesses could be discovered among samples, yet a substantial portion of the site is above the cleanup standard. This is clearly not a desirable environmental result. With small sample sizes, the chance of missing detection of contamination is greater than with larger sample sizes. This is intuitive; the more you search for contamination and do not find it, the more confident you become in your conclusion that the site is clean. Clearly, because of the extrapolation exercise, the statements or inferences regarding the 10 million sample locations have uncertainty. Statistical methods enable estimation of the uncertainty. Without the statistical methods, uncertainty still exists; but the uncertainty cannot be estimated validly. A specific sampling and data analysis protocol must accompany the risk-based standard for the standard to be meaningful in terms of benefit or actual risk. (U.S. EPA, 1992; U.S. EPA, 2000) This study describes methods for testing whether soil chemical concentrations at a site are statistically below a cleanup standard. If it can be reasonably concluded that the treated soil at a site has metal concentrations statistically less than the relevant cleanup standards, the site can be judged as having had a successful cleanup.

II. MATERIALS AND METHODS

A continuous probability distribution can be displayed in a graph in the form of either a PDF or corresponding CDF. Both displays represent the same distribution, but are useful for conveying different information. The CDF for risk can be especially informative for illustrating the percentile corresponding to a particular risk level of concern. This paper proposes a verification method using the CDF curve. The shape of the CDF curve for an ideal performance would be a step function that has a 1.0 probability of declaring the site clean whenever the true concentration is less than the cleanup standard and a zero probability of declaring the site clean when the concentration is greater than the cleanup standard. However, in reality there were still some variations observed among samples so that the CDF curve was S-shaped. The performance of remediation work could be evaluated by the CDF curve, as a realistic curve getting closer to the step function which indicated remediation efforts had been more successful.

1. Fitting Distributions to Data

Sometimes more than one probability distribution may adequately characterize variability or uncertainty. The choice of a distribution should be based on the available data and on knowledge of the mechanisms or processes that result in variability. In general, the preferred choice is the simplest probability model that adequately characterizes variability or uncertainty and is consistent with the mechanism underlying the data. The first step is to fit the best distributions for the data set. For sample data, distribution parameters are estimated using Maximum Likelihood Estimators (MLEs). The MLEs of a distribution are the parameters of that function that maximize the probability of obtaining the given data set. Sample (or observation) data is a set of values drawn from a large population. Distributions are fit to sample data to estimate the characteristics of that population.

A lot of statistical computer software is commercially available. @RISK was used in this study. To start the fitting process, we tried to find the set of parameters that gave the closest match between the distribution function and the data set. However, @RISK did not produce an absolute answer, but rather identified a distribution that most likely produced the given data.

2. Develop the Cumulative Probability Distribution (CDF) Curve

Once the distribution of samples has been identified, then the probability density distribution function (PDF) curve and corresponding cumulative probability distribution (CDF) curve can be developed for the data set. Examples given in Fig. 1 are the PDF and CDF curves for lognormal distribution and triangular distribution, respectively. The types of information that PDFs and CDFs are most useful for displaying are: PDF (1) the relative probability of values; (2) the most likely values (e.g., modes); (3) the shape of the distribution (e.g., skewness, kurtosis, multimodality); and (4) small changes in probability

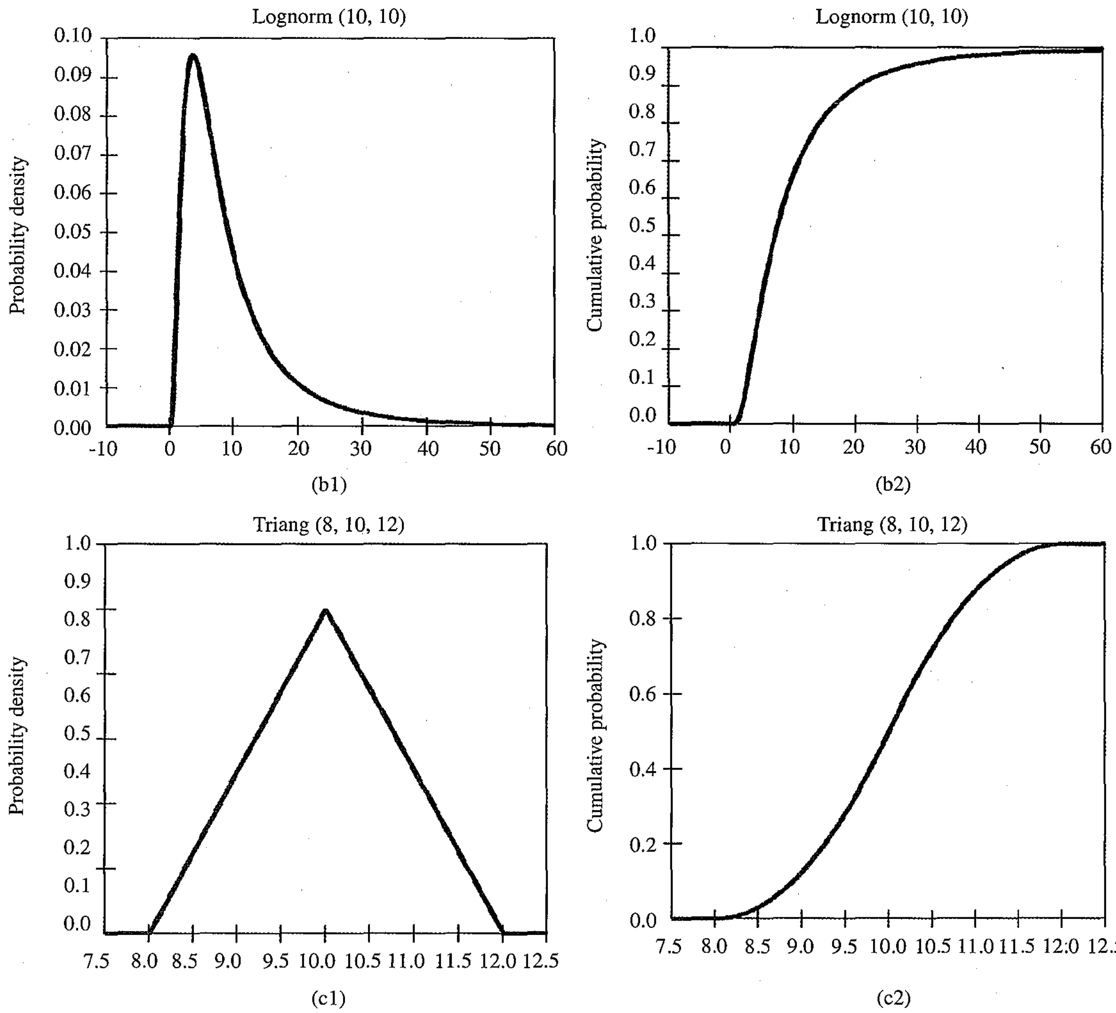

Fig. 1 Examples of lognormal distribution and triangular distribution that characterize variability in heavy metal content of soil samples. The left panels show curves representing the PDF, while the right panels show S-shaped curve representing the CDF.

density and for CDF: (1) Percentiles, including the median; (2) high-end risk range (e.g., 90th to 99th percentiles); (3) confidence intervals for selected percentiles; and (4) stochastic dominance (i.e., for any percentile, the value for one variable exceeds that of any other variable). (US EPA, 2001)

3. The Data

Many field and pot experiments on soil remediation techniques have been conducted at Chung-Fu and Hau-Tan polluted sites (Chen *et al.*, 1994; Lee and Chen, 1994; Chen and Lee, 1997; Wang, 1996; Chen, 2001). The soil remediation techniques include: (1) chemical stabilization method to reduce the solubility of heavy metals by adding some non-toxic materials into the soils, (2) removal of polluted surface soils and replacement with clean soils, (3) covering the original polluted soil surface with clean soils, (4) on-site chemical leaching with acid agents, and (5) use of dilution, mixing polluted soils with surface and subsurface clean soils to reduce the concentration of heavy metals, or (6) phytoremediation by plants such as woody trees. The dilution method has been widely used as the remediation technique for these contaminated sites. In this study, the analytical data of soil samples from Chung-Fu and Hua-Tan remediation projects (Chen, 2001; Wang, 1996) are summarized in Tables 1 to 3 and the sampling locations are shown in Figs. 2 and 3.

III. RESULTS AND DISCUSSION

1. Guideline for Verifying the Attainment of Soil Remediation

In Taiwan, the current verification method requires that a contaminated site be cleaned until the

Table 1 Data summary of Chung-Fu remediation project Soil: Cd concentration of samples from Site 1 before refill (mg/kg, 0.1M HCl extractable)

Location	Upper layer	Medium layer	Bottom layer
1-1	0.75	0.74	0.60
1-2	0.86	0.77	0.44
1-3	0.70	0.58	0.52
1-4	0.84	1.46	0.74
1-5	0.83	1.32	0.59

chemical concentration of every soil sample drops below the control standard. The advantage of this method is easily described and communicated and it requires less time to complete the verification process. Disadvantages of this method include: (1) its simplifications may result in deviations from the target values; (2) its results are often viewed as "the answer", thus the importance of the inherent uncertainty is lost; (3) it does not provide a measure of the probability that risk could exceed the target level of concern; (4) it provides fewer incentives for collecting better or complete information needed; and (5) it may not utilize all data available for characterizing variability and uncertainty in decision making.

In the United States, when dealing with a Superfund site, verification usually involves performing appropriate statistical analysis in order to decide whether the site requires additional cleanup. The hypotheses considered are:

Case 1: H_0: $\mu \le C$ vs. H_A: $\mu > C$; and
Case 2: H_0: $\mu \ge C$ vs. H_A: $\mu < C$

where C represents a given threshold such as a regulatory level, and μ denotes the (true) mean contaminant level for the population. For example, C may represent the cadmium concentration level of concern. The information required for this test includes the null and alternative hypotheses; the gray region, i.e., a value $\mu1 > C$ for Case 1 or a value $\mu1 < C$ for Case 2 representing the bound of the gray region; the false rejection error rate α at C; the false acceptance error rate β at $\mu1$; and any additional limits on decision errors. The one-sample t-test is used to test hypotheses involving the mean (μ) of the population from which the sample was selected.

As we adopted the same method for Taiwan, few obstacles were encountered. The tolerable decision error rates could not be established; the sample size was determined by budget, usually far below the number needed for achieving the levels of the false rejection and false acceptance error rates test; and it was adversely affected by outliers or less-than-detection-limit values because only a few data values were available.

2. Ideal and Realistic Performance CDF Curves

This paper proposes a technical guideline for evaluating the success of soil remediation efforts by using the CDF curve. Assuming that the turnover and mixing were performed thoroughly in the remediation process, all the soil at a site would have the same concentration regardless of from where the samples were taken. And the CDF curve of an ideal performance would be a step function in shape that has a 1.0 probability of declaring the site clean whenever the true concentration is less than the cleanup standard and a zero probability of declaring the site clean when the concentration is greater than the cleanup standard. However, in reality there were still some variations observed among samples so that the CDF curve was S-shaped as shown in Fig. 4. The performance of remediation work could be evaluated by the CDF curve, as a realistic curve getting closer to the ideal curve which indicated remediation efforts had been more successful.

The proposed guideline contains four parameters. The first parameter is that the concentration of every sample must be less than the control standard. The second parameter is the 97.5th percentile is not to exceed the control standard. The third parameter is that the 50th percentile of the samples is below the monitoring standard. The fourth parameter is the indicator of concentration evenness for remediation work, the ratio of C_{75} to C_{25} must be less than 2. The rationale of each parameter is presented in Table 4 and discussed below:

Parameter 1, X_i<control standards: "Soil And Groundwater Pollution Control Act" stipulates that as the pollutant concentration within the soil of a site exceeds the soil pollution control standards, local authorities shall declare it a soil pollution control site. On the contrary, no excesses should be detected at a fully remediated site.

Parameter 2, $C_{97.5}$<control standards: When specifying control site remediation objectives in consent decrees, it is extremely important to say that the site shall be cleaned up until the sampling program indicates, with reasonable confidence, that the concentrations of the contaminants at the entire site are statistically less than the control standards. This prescription will result in the site being designated clean only after a situation similar to "$C_{97.5}$<control standards" is observed. However, attainment is often wrongly described by saying that concentrations at the site shall not exceed the control standard.

Table 2 Data summary of Chung-Fu remediation project soil Cd and Pb: concentration of samples from Site 3 after mixing and compaction (mg/kg, 0.1M HCl extractable)

Location	II-3-1			II-3-2			II-3-3				II-3-4				
Depth (cm)	0-15	15-30	30-60	0-15	15-30	30-60	0-15	15-30	30-60	60-90	0-15	15-30	30-60	60-90	90-120
Cd (mg/kg)	0.73	0.78	0.72	0.68	0.69	0.21	0.30	0.26	0.21	0.23	0.41	0.35	0.42	0.51	0.24
Pb (mg/kg)	9.04	9.91	9.77	8.69	8.78	6.86	7.18	12.96	6.64	6.65	8.22	8.00	8.21	8.63	8.63

Location	II-3-5			II-3-6			II-3-7			II-3-8		
Depth (cm)	0-15	15-30	30-60	0-15	15-30	30-60	0-15	15-30	30-60	0-15	15-30	30-60
Cd (mg/kg)	0.28	0.22	0.24	0.82	0.76	0.68	0.23	0.42	0.46	0.35	0.22	0.20
Pb (mg/kg)	7.70	7.78	7.48	10.19	10.25	11.46	8.04	6.88	8.16	8.69	7.25	8.04

Location	II-3-9					II-3-10					II-3-11			
Depth (cm)	0-15	15-30	30-60	60-90	90-120	0-15	15-30	30-60	60-90	90-120	0-15	15-30	30-60	60-90
Cd (mg/kg)	0.36	0.38	0.33	0.21	0.23	0.37	0.39	0.63	0.65	0.10	0.63	0.08	0.38	0.46
Pb (mg/kg)	7.11	8.19	8.01	7.52	6.66	8.50	7.61	7.36	7.59	5.84	9.75	4.99	8.95	8.87

Location	II-3-12				II-3-13					II-3-14				
Depth (cm)	0-15	15-30	30-60	60-90	0-15	15-30	30-60	60-90	90-120	0-15	15-30	30-60	60-90	90-120
Cd (mg/kg)	0.56	0.59	0.73	0.54	0.57	0.90	0.88	0.68	0.19	0.36	0.26	0.16	0.11	0.12
Pb (mg/kg)	9.85	10.54	11.31	11.04	9.66	10.49	11.75	10.10	8.64	8.16	8.64	20.06	7.24	25.53

Location	II-3-15			II-3-16			II-3-17			II-3-18				
Depth (cm)	0-15	15-30	30-60	0-15	15-30	30-60	0-15	15-30	30-60	0-15	15-30	45-60	60-90	0-15
Cd (mg/kg)	0.92	0.92	0.87	0.75	0.52	0.09	0.62	0.54	0.51	0.29	0.76	0.76	0.22	0.34
Pb (mg/kg)	8.58	9.24	8.84	7.76	8.05	5.54	7.76	9.26	7.81	12.00	12.37	12.25	12.77	12.97

Location	II-3-19				II-3-20		
Depth (cm)	15-30	30-60	60-90	90-120	0-15	15-30	30-60
Cd (mg/kg)	0.65	0.44	0.30	0.29	0.26	0.25	0.22
Pb (mg/kg)	15.33	13.27	17.88	15.81	14.17	13.98	13.64

Table 3 Data summary of Hua-Tan remediation project soil: Cd concentration of samples from Site 2 after turnover and mixing (mg/kg, 0.1M HCl extractable)

Sample no.	Cd mg/kg	Sample no.	Cd mg/kg	Sample no.	Cd mg/kg	Sample no.	Cd mg/kg
01-U	0.22	07-B	0.21	14-U	0.34	20-U	0.07
01-B	0.12	08-U	0.12	14-B	0.16	20-B	0.31
02-U	0.21	08-B	0.09	15-U	0.29	21-U	0.24
02-B	0.11	09-U	0.07	15-B	0.10	21-B	0.12
03-U	0.04	09-B	0.08	16-U	0.02	22-U	0.12
03-B	0.01	10-U	0.20	16-B	0.12	22-B	0.10
04-U	0.10	10-B	0.17	17-U	0.02	23-U	0.04
04-B	0.20	11-U	0.37	17-B	<.01	23-B	0.12
05-U	0.09	11-B	0.54	18-U	0.13	24-U	0.01
05-B	0.21	12-U	0.32	18-B	0.12	24-B	0.24
06-U	0.26	12-B	0.54	19-U	0.05	25-U	0.26
06-B	0.12	13-U	0.40	19-B	0.05	25-B	0.38
07-U	0.13	13-B	0.63				

U: surface layer 0-15cm B: subsurface layer 15-30cm

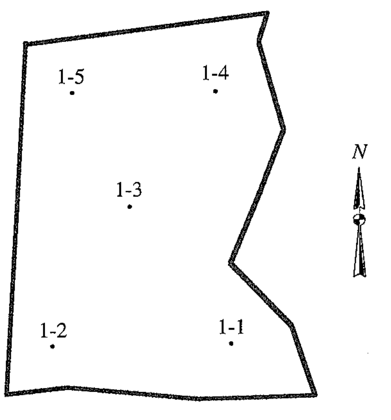

Fig. 2 Sampling locations of Site 1 in Chung-Fu remediation project (site area 1,884m^2)

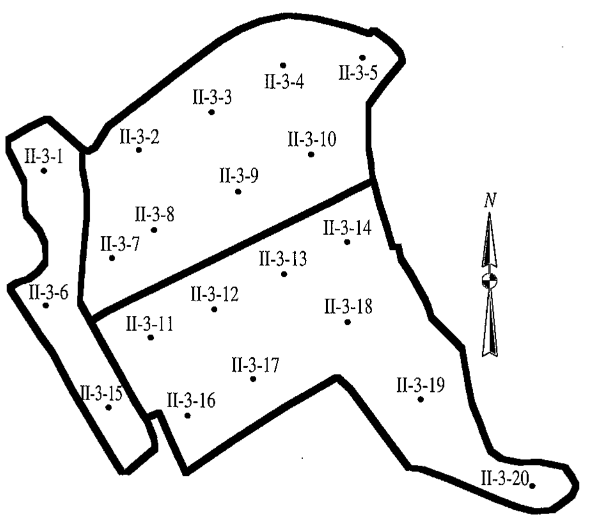

Fig. 3 Sampling locations of Site 3 in Chung-Fu remediation project (site area 19,416m^2)

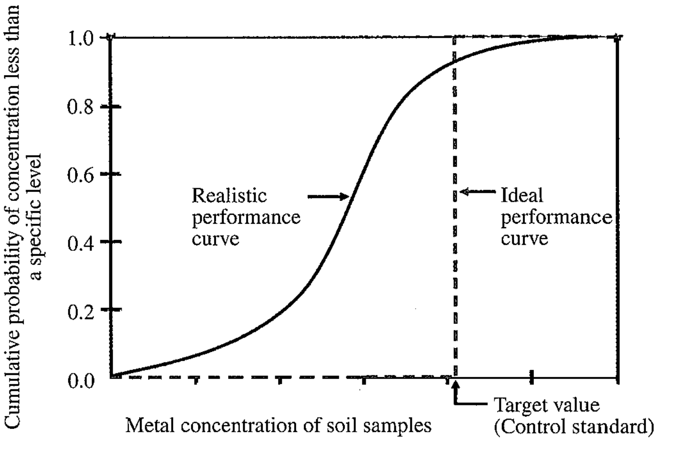

Fig. 4 Ideal and realistic performance CDF curves for soil remediation work

Parameter 3, C_{50}<monitoring standards: Article 6 of the "Soil And Groundwater Pollution Control Act" states that: If pollutant concentrations are lower than the soil pollution control standards but exceed the soil pollution monitoring standards, local authorities shall conduct routine monitoring, declare the monitoring results and report to the central competent authority for their reference. Therefore, the requirement of C_{50} (median) below than monitoring standard is important; otherwise, the routine monitoring shall be conducted after remediation.

Parameter 4, C_{75}/C_{25}<2.0 In an attempt to determine whether the concentration variations are acceptable in soil samples. This parameter represents the evenness and completeness, which is an indicator of working quality.

Table 4 Proposed verification guideline for the attainment of soil remediation works

Parameter	Goal	Rationale
X_i<control standard	No excess will be detected	Regulations
$C_{97.5}$<control standards	97.5th percentile less than control standards	To guard against the small sampling size
C_{50}<monitoring standards	50th percentile below monitoring standards	Prevent exceeding the monitoring standards otherwise the monitoring shall be conducted regularly afterward
C_{75}/C_{25}<2.0	Evenness and completeness	Quality control for remediation works

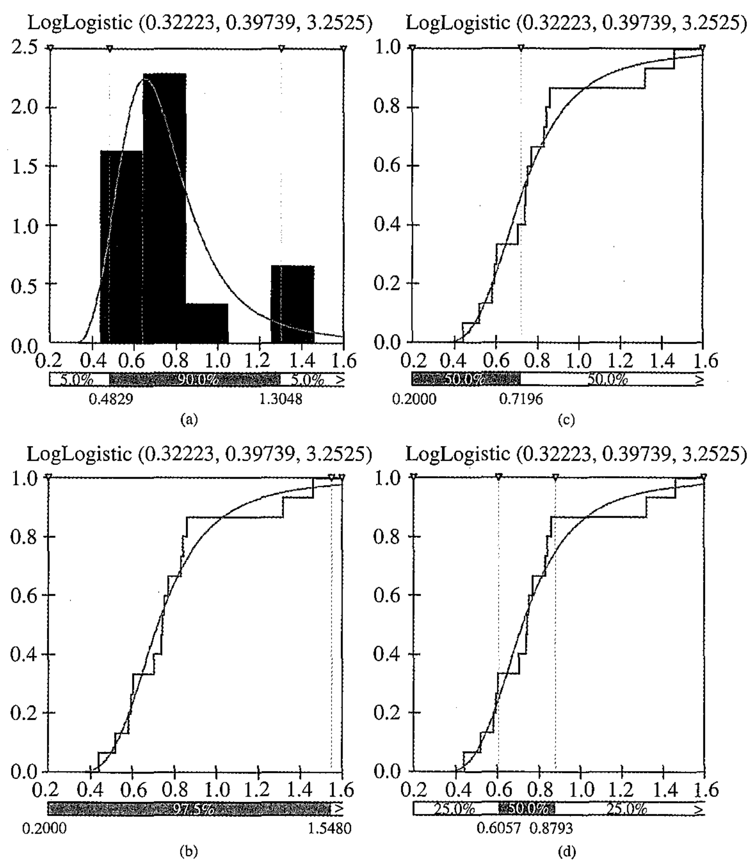

Fig. 5 (a) Data fitting for the selected distribution, (b) $C_{97.5}$ (c) C_{50} (d) C_{75} and C_{25} for Case 1

3. Case Study

Chang-Hwa and Tao-Yuan counties have been regarded as the most seriously heavy metal polluted areas in Taiwan. In these two counties, some local sites might be polluted by wastewater from industrial plants that has been distributed through irrigation systems. Chang *et al.* (1999), Lin and Chang (2000) and Lin *et al.* (2001) have reported that the local spatial patterns of heavy metal soil pollution are related significantly to the locations of industrial plants and irrigation systems. For the past 20 years, many efforts have been made to revitalize contaminated farmland using limited resources. Dilution through turnover and mixing is widely used as the remediation technique. In this study, four cases selected from two projects were chosen to test the suitability of our proposed guideline.

Case 1. The Cd concentration data were collected from Chung-Fu remediation project Site 1, summarized in Table 1. At the five locations, soil samples were taken from three soil layers before the refill and compaction. Data was best fit to log-logistic distribution as shown in Fig. 5(a). CDF curve was established while

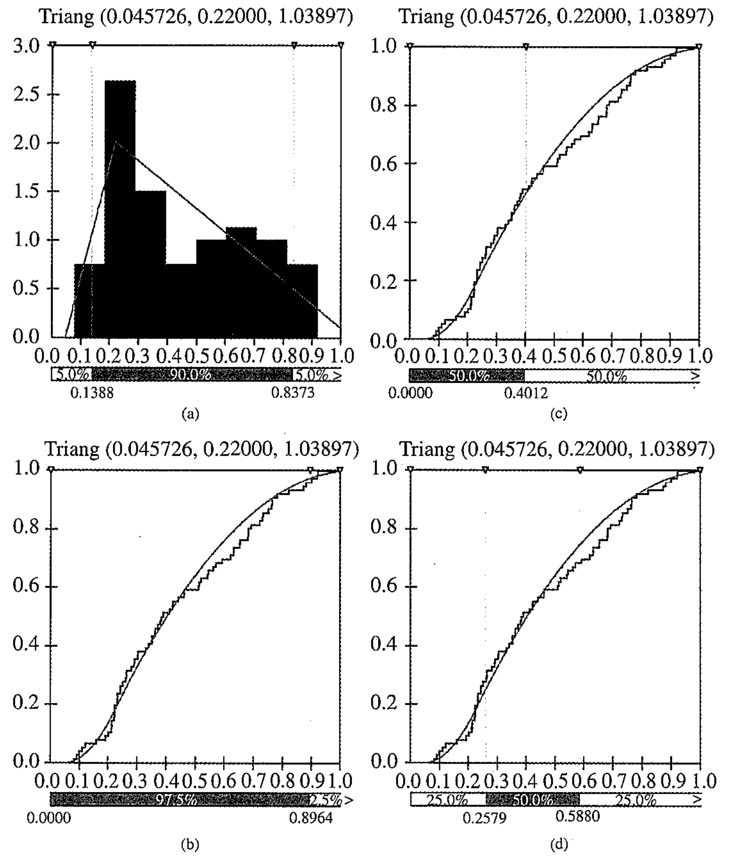

Fig. 6 (a) Data fitting for the selected distribution, (b) $C_{97.5}$ (c) C_{50} (d) C_{75} and C_{25} for Case 2

the figures of $C_{97.5}$, C_{50}, C_{75} and C_{25} were drawn according to the curve, as displayed in Figs. 5(b), 5(c) and 5(d) respectively.

Case 2. The Cd concentration data were collected from Chung-Fu remediation project Site 3, summarized in Table 2. Soil samples were taken from 20 locations after the refill and compaction. Data was best fit to triangular distribution as shown in Fig. 6(a). CDF curve was established while the figures of $C_{97.5}$, C_{50}, C_{75} and C_{25} were drawn according to the curve, as shown in Figs. 6(b), 6(c) and 6(d) respectively.

Case 3. The Pb concentration data were collected from Chung-Fu remediation project Site 3, summarized in Table 2. Soil samples were taken from 20 locations after the refill and compaction. Data was best fit to log-logistic distribution as shown in Fig. 7(a). CDF curve was established while the figures of $C_{97.5}$, C_{50}, C_{75} and C_{25}were drawn according to the curve, as shown in Figs. 7(b), 7(c) and 7(d) respectively.

Case 4. The Cd concentration data were collected from Hua-Tan remediation project Site 2, as summarized in Table 3. Soil samples were taken from 25 locations after the turnover and mixing. Data was best fit to log-logistic distribution as shown in Fig. 8(a) CDF curve was established while the figures of $C_{97.5}$, C_{50}, C_{75} and C_{25} can be drawn according to the curve, as shown in Figs. 8(b), 8(c) and 8 (d) respectively.

4. Results

Figures 5(a), 6(a), 7(a) and 8(a) display the distributions of samples that had been fitted closest to match the distribution function with the data set by @RISK statistical software. There are three types of distribution in 4 cases that were most likely produced from the given data. Results shown in Figs. 5(b), 6(b), 7(b) and 8(b) indicate the values of 97.5th percentile in cumulative probability distribution (CDF) curves; in other words, the probability of any other sampling result less than this concentration would be 97.5%. Results shown in Figs. 5(c), 6 (c), 7(c) and 8(c) indicate the values of the samples 50th percentile of concentration in CDF curves; in other words, the probability of any other sampling result being less

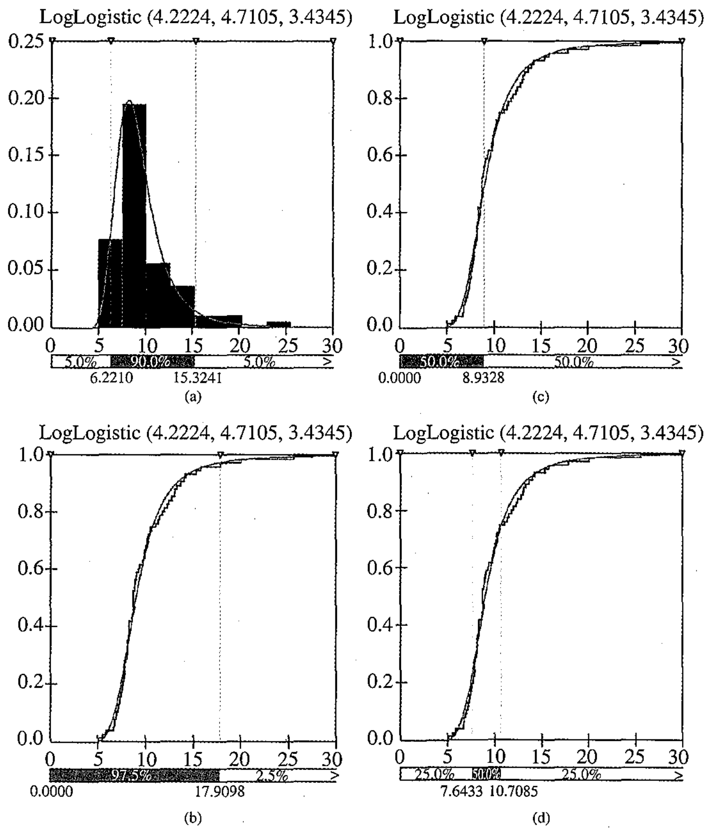

Fig. 7 (a) Data fitting for the selected distribution, (b) $C_{97.5}$ (c) C_{50} (d) C_{75} and C_{25} for Case 3

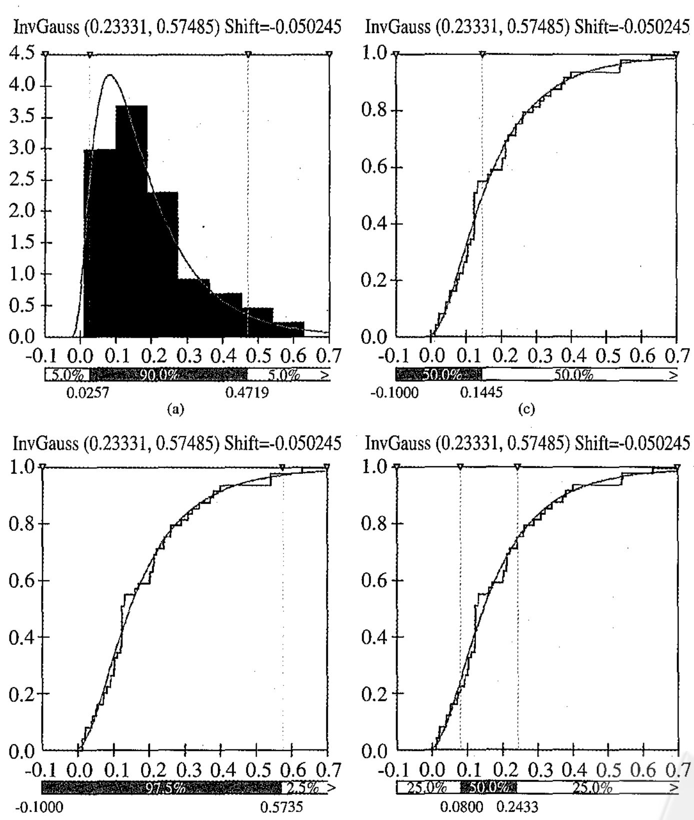

Fig. 8 (a) Data fitting for the selected distribution, (b) $C_{97.5}$ (c) C_{50} (d) C_{75} and C_{25} for Case 4

Table 5 Test results of 4 cases for the proposed guideline

Case no.	Parameter	Comparison	Remark
Case 1	X_i<1.0	0.44~1.46	rejected
	$C_{97.5}$<1.0	1.55	rejected
	C_{50}<0.5	0.72	rejected
	C_{75}/C_{25}<2.0	0.88/0.61=1.45	accepted
Case 2	X_i<1.0	0.09~0.92<1.0	accepted
	$C_{97.5}$<1.0	0.90<1.0	accepted
	C_{50}<0.5	0.40<0.5	accepted
	C_{75}/C_{25}<2.0	0.59/0.26=2.28	rejected
Case 3	X_i<40.0	4.99~25.53<40.0	accepted
	$C_{97.5}$<40.0	17.91<40.0	accepted
	C_{50}<20.0	8.93<20.0	accepted
	C_{75}/C_{25}<2.0	10.71/7.64=1.40	accepted
Case 4	X_i<1.0	0.01~0.63<1.0	accepted
	$C_{97.5}$<1.0	0.57<1.0	accepted
	C_{50}<0.5	0.14<0.5	accepted
	C_{75}/C_{25}<2.0	0.24/0.08=3.0	rejected

than this concentration would be 50%. Results displayed in Figs. 5(d), 6(d), 7(d) and 8(d) show the values of C_{75} and C_{25} in CDF curves, respectively, and the ratio of C_{75} and C_{25} is an indicator of evenness.

The cleanup standard of Cd used in Cases 1, 2 and 4 was 1.0 mg/kg, and the cleanup standard of Pb in Case 3 was 40 mg/kg; in all cases the monitoring standards used were one-half of the cleanup standards. Table 5 shows the test results from each case. In Case 1, 3 out of the 4 parameters were rejected, because sampling was done after the turnover and before the refill and compaction. The procedure was meant to ensure that mixing is thorough. Unfortunately, the result from using this procedure did not meet the traditional cleanup standard nor the proposed guideline. In the Cases 2, 3 out of the 4 parameters were accepted and only the evenness indicator was rejected. As we examined the data set further, we found that the Cd concentration ranging from 0.09 to 0.92 mg/kg reflected an incomplete mixing procedure. In Case 3, all the criteria were satisfactory, showing that the remediation effort was successful. In Case 4, the evenness indicator was rejected, revealing that the mixing procedure needed to be enhanced.

Test results of the above 4 cases showed that the proposed guideline was evaluated effective as to verifying the attainment of soil remediation. The proposed guideline, as compared with the current verification method adopted in Taiwan, has three major advantages: (1) it can make more complete use of available data when defining attainment of soil remediation; (2) it can provide a more comprehensive characterization of variability and uncertainty in risk estimates; and (3) it can support statements regarding confidence in risk estimates to help to build trust among stakeholders.

IV. CONCLUSIONS

Developing an effective guideline is a crucial step for scientific decision making. The primary advantage of the proposed guideline is that all the available data has been fully utilized for characterizing variability and uncertainty; therefore, a quantitative description of the degree of uncertainty on the attainment of soil remediation can be made when making decisions regarding the entire site. Here, quantitative analysis of uncertainty and variability can provide a more comprehensive characterization of risk than is possible in the traditional approach. By four cases, our proposed guideline is shown to be effective in verifying remediation results. In comparison with the traditional method, although the same data set is used for making a judgment, we feel more confident in our proposed guideline when it comes time to make a decision.

NOMENCLATURE

C the cleanup standard relevant to the sample area and the contaminant being tested

CDF the cumulative probability of occurrence for a random independent variable

C_n the chemical concentration of n^{th} percentile to a relevant CDF

H_0 the null hypothesis is that the sample area does not attain the cleanup

H_A the alternative hypothesis, which is declared to be true only if the null hypothesis is shown to be false based on significant contradictory data

PDF a function representing the probability distribution of a continuous random variable

X_i the chemical concentration measured for soil sample

α the desired false positive rate for the statistical test

β the false negative rate for the statistical test

μ the population mean

μ_1 the value of μ under alternative hypothesis for which a specified false negative rate is to be controlled

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