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Project Summary

Assessment of Hazardous Waste Surface Impoundment Technology: Case Studies and Perspectives of Experts

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Nine hazardous waste surface impoundments (SI's) were assessed in a case study to compare actual and projected performances. The goal was to produce data that can significantly improve the design, construction, and operation of these facilities. The nine facilities represent a range of industries, waste types and volumes, ages, environmental settings, linear types and designs, and systems for leak detection and groundwater monitoring.

In addition to the case studies, nine interviews were held with technical experts in four consulting engineering firms, one waste management company, one liner fabricator and installer, and regulatory agencies in three states. Recommendations for research and development are presented based on the case studies and the professional opinions collected.

The poor performances of several SI's were attributed to factors such as lack of good project planning during design and construction, lack of quality assurance and control, deviations from liner specifications, inadequate waste-liner compatibility studies, and lack of proper site investigations before design and construction. The successful performances of SI's at two facilities are attributable to the use of a very impermeable clay liner after extensive compatibility studies; use of competent contractors; close scrutiny of all phases of design, construction, and inspection by the owner/operator; excellent quality assurance and control recordkeeping; and good communication among all parties involved.

Technical experts consider the following factors essential to good site performance: Siting in good geologic formation, continuous geotechnical support throughout all project phases, supervised construction to ensure adherence to specifications, compaction of clay liner wet of optimum to eliminate air spaces, consideration of liner-waste compatibility, rigorous quality assurance and control in designing and installing liners, and provision and maintenance of protective covers for liners.

Research and development areas should include documenting and disseminating design and performance data from operating sites, evaluating waste-liner compatibility under actual conditions, developing reliable techniques for early detection of site failure, establishing criteria for groundwater monitoring systems, and studying the causes and cures for plugged leachate collection systems in landfills.

This Project Summary was developed by EPA's Hazardous Waste Engineering Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

A research project was undertaken to investigate the use of surface impoundments (SI's) for hazardous waste management. The primary goals were to develop criteria for improved SI design and operation and to provide technical support to the U.S. Environmental

Protection Agency (EPA) in developing SI regulations as required by the Resource Conservation and Recovery Act (RCRA).

Currently, the principal source of EPA information on hazardous waste SI's is the surface impoundment assessment (SIA) data base developed by the Office of Drinking Water. Though the data base contains some background survey information on the numbers, types, and uses of wastes handled by municipal, industrial, and agricultural SI's in the United States, it contains little or no information on their engineering design and actual performance. Comparing projected and actual performances at operating SI's and identifying reasons for observed differences are essential for designing better SI's and for formulating appropriate corrective actions at existing sites.

The present study therefore develops a data base on hazardous waste SI design and operating practices and compares actual and projected performances for a selected number of facilities. The study identifies gaps in the existing data base and in areas that most warrant research and development.

Two complementary approaches are being used to define the state of the art for hazardous waste SI technology: Case studies for a selected number of SI's and interviews with technical experts.

Case Studies

The SI's for the case studies were selected largely from those operating in the southwestern United States, primarily California and Texas. Twenty-eight facilities were selected as potential candidates for case studies based on examinations of state data files, state SIA surveys, and background data from other recent hazardous waste management projects. These sites were further screened by discussions with state regulatory agencies and facility owners/operators, and by considering the following factors:

- Amount of data available
- Representation of a range of SI service types
- Presence and type of liner used
- Types of hazardous waste handled
- Design and construction practices
- Facility performance
- Absence of litigation
- Anticipated level of cooperation from owner/operator

The preliminary screening eliminated eight sites from further consideration because of multiple potential sources of pollution, ongoing litigation, and lack of operating data at new sites. Further screening eliminated 11 additional sites, and detailed case study and assessment summary reports were prepared for the remaining nine sites.

The nine cases were evaluated in some detail, and case study and assessment summary reports were prepared. Table 1 contains general information on these sites, including the types and qualities of wastes handled. As noted in the table, these SI's serve a variety of industries, handle different waste types and volumes, are used for disposal or treatment purposes, and range in age from less than 2 to more than 30 years. The case studies cover a range of liner types and designs—single liners, double liners, clay liners, flexible membrane liners (FML's), and clay liners used with FML's. A variety of leak detection systems are also examined. The extent of groundwater monitoring also varies from the use of no observation wells to the use of multiple wells at strategic locations.

The case study report prepared for each site essentially compiles all available relevant data for that site and is the basis for performance assessment. For each facility, the draft case study report was submitted to the site owners/operators for review to assure accuracy and completeness and to provide them with an opportunity to expand or supply additional information or clarifications. In transmitting the draft reports, the owners/operators were requested to provide any quantitative engineering data (e.g., on the original site design, actual construction, liner inspection, and maintenance programs) that might support some of the qualitative statements and assertions. Comments received from the reviewers were incorporated in the case study reports as appropriate.

The identity of the case study sites was of little consequence to the project objective. Thus to promote the cooperation of the owners/operators, all sites were kept anonymous and designated only by letter or number.

Interviews and Experts

This phase of the study sought the perspective of experts on factors affecting SI performance and deviation from design predictions. Information was gathered from those most intimately involved in the design, construction, operation, and regulation of hazardous waste SI's. Though a large number of individuals and organizations were contacted, only nine granted interviews. Except for one interview conducted with a written questionnaire, discussions were face to face in a very informal atmosphere. In most cases, more than one individual represented the participating organization. Discussions generally covered some or all of the following topics:

- Surface impoundment versus landfill
- Site selection
- Geotechnical evaluation
- Design criteria and considerations
- Quality assurance and quality control
- Liner material selection and liner-waste compatibility problems
- Site preparation and liner installation
- Research and development needs
- Regulatory considerations

A summary report was prepared after the interview and forwarded to the participants for review and comment. Suggested changes, which were generally minor, were all incorporated in the final report.

Results

Detailed evaluation of the data compiled for the nine cases studied has resulted in the following assessments.

Case Study No. 1

The two FML-lined hazardous waste SI's at this site were designed and constructed by the owner in 1972 and 1979. Since no regulatory requirements governed the design or construction of such facilities at the time, no geotechnical or hydrogeological studies, environmental impact analysis, or laboratory or field investigations preceded the actual design and construction. Onsite availability of land was the primary consideration for SI site selection. Apparently, no rigorous quality assurance and control (QA/QC) program was conducted, nor was there any inspection of the completed SI's by professionals trained in FML design and installation.

The SI's at this site have failed to provide satisfactory service. Limited water quality data from monitoring and production wells indicate contamination of both the upper and the lower groundwater aquifers, as evidenced by increases in the total dissolved solids, sulfate, and nitrate concentrations. Because cracks appeared along the exposed sides of the liner in one of the ponds, the liner was replaced once. Possibly the liners in both ponds are now leaking. Because of the relatively high permeability of the geological strata underlying the plant (0.44×10^{-2} to 1.4×10^{-2} cm/sec) and the strong acidic nature of the heavy metal-bearing waste in the SI's, any liner failure could result in a substantial underground waste release. Hence the site presents major potential for groundwater contamination.

Table 1. *Case Study Facilities - General Features and Waste Characteristics*

Case Study No.	Type of Facility	Type of SI (No. and Function)	Year Placed in Service	SI Size (Acres)	Waste Type	Waste Quantity
1	Electrolytic metal refining plant	Small disposal pond	1972	0.4	Acidic process liquor and sludge waste (pH <2) high in heavy metal content	A total of 843,750 gal in 1982
		Disposal pond	1979	1.1	Acidic process liquor and sludge waste (pH <2) high in heavy metal content	
2	Pesticide formulation and distribution plant	Pesticide washdown evaporation disposal pond	1979	<0.1	Pesticide rinsewater	Batch operation (400 gal/day maximum)
		Pesticide rinsewater evaporation disposal pond	1982	<0.1	Pesticide rinsewater	Batch operation (400 gal/day maximum)
3	Commercial hazardous waste disposal facility	Site A: 8 impoundments used for settling, storage, and sludge disposal	1951	15	Oily water and brines, alkaline and acid wastes, heavy metals paint sludge, tank bottom sediments, cyanide, pesticides, and other chemical wastes	A total of 53 million gal in 1982
4	Agricultural fertilizer manufacturing plant	11 settling ponds used to remove gypsum	1965	14	Production water for ammonium phosphate/phosphoric acid plant with pH <2 and high radionuclides content	20,000 gal/day
		One evaporation pond (treatment)	1976	8	Wastewaters from plant boilers, water treaters, and nitric and sulfuric acid plants (pH<2, high in radionuclides)	130,000 gal/day
		One cooling pond (treatment)	1976	38	Same as gypsum SI's	10,000 gal/day
5	Mineral ore mining/ manufacturing plant	5 low-head solar ponds (treatment and storage)	1972	90	Mineral liquor tailings with high arsenic and boron content	A total of 50 million gal/month to Ponds A-E, 4, and 5
		High-head evaporation pond (treatment and storage)	1975	80	Mineral liquor tailings with high arsenic and boron content	
		High-head evaporation pond (treatment and storage)	1976	100	Mineral liquor tailings with high arsenic and boron content	
		Evaporation pond (treatment and storage) high arsenic and boron content	1980	120	Acid plant wastewater with high arsenic and boron content	12 million gal/ month
6	Commercial hazardous waste disposal facility	Evaporation pond (disposal)	1980	5	Geothermal muds and brines, wastewater treatment sludge, tank bottom sediments, cooling tower blowdown sludge and oil drilling muds	9.85 million gal in 1982
		Disposal pond (currently used for land treatment)	1980	5	Geothermal muds and brines, wastewater treatment sludge, tank bottom sediments, cooling tower blowdown sludge, and oil drilling muds	
		Disposal pond (currently)	1981	5	Geothermal muds and brines, wastewater treatment sludge, tank bottom sediments, cooling tower blowdown sludge and oil drilling muds	

7	*Agricultural fertilizer manufacturing plant*	*Cooling pond (treatment)*	*1974*	*100*	*Process water from phosphoric acid plant with pH <2 and high fluoride content*	*40,000 gal/min (maximum)*
		Initial gypsum pond (disposal)	*1974*	*150*	*Gypsum slurry with pH <2 and fluoride and phosphorus content*	*No data available*
		Expansion gypsum pond (disposal)	*1980*	*200*	*Gypsum slurry with pH< 2 and fluoride and phosphorus content*	*No data available*
8	*Chemical production plant*	*2 equalization/retention basins (treatment)*	*1976*	*3.5*	*Wastes high in organic nitrogen content and varying pH, resulting from synthetic fiber production*	*3,000 gal/min*
9	*Uranium mining/ milling*	*Tailings pond (disposal)*	*1980*	*64*	*Acidic tailings slurry containing kerosene and radium 226*	*No data available*

Case Study No. 2

The very satisfactory operation at this site indicates that with proper site and wastewater characteristics, designing and constructing small ponds to provide satisfactory performance can be simple tasks.

Two very small (48 x 28 x 5 ft and 30 x 20 x 3 ft), relatively new, onsite impoundments serve this pesticide formulation and packaging plant, which generates intermittent discharges of wash-down and rinse water. The waste volume is very small, seldom exceeding 400 gal per discharge two to three times per month. Groundwater in the area is at 215 ft. The wash-down pond is lined with two layers of polyvinyl chloride (PVC) sheeting as the primary liner on both the bottom and the side slopes. A 30-mil PVC liner is used as the secondary liner on the bottom only. The primary and secondary liners are separated by 1 ft of gravel. The rinse-water pond is lined with 20-mil chlorinated polyethylene (CPE) underlain with 1 ft of sand and a 10-mil PVC liner, with both liners extending along the bottom and side slopes. The leak detection system for each pond is merely a single, perforated PVC pipe (a 3-in. pipe for the wash-down pond and 1-in. pipe for the rinse-water ponds) extending halfway across the pond bottom and connecting to an observation well. A 1/4-in. fiber glass cover was recently placed over the primary liner in each pond for better protection against liner deterioration and damage during pond cleaning. A 20,000-gal storage and equalization tank was also recently installed to control liquid level in the wash-down tank.

During the 4-year operation of the wash-down pond, no liquid was observed in the observation well. Since the rinse-water pond was placed in operation only in late 1982, similar results from the leak detection have not yet been reported.

Case Study No. 3

The two impoundments located in separate areas of this facility exemplify the performance differences between poorly planned and designed ponds and those that are well planned. Problems resulting from poor planning cannot always be fully and permanently corrected through piecemeal remedies. This fact is illustrated at Site A, where nothing indicates that detailed site selection investigations or pond design took place. When the facility was investigated in 1971, wastes were seeping through pond levees that had been built on top of old waste fill. Work was performed to correct the problem at that time, but seepage was reported again during investigations in 1978. Specific levee permeability and thickness requirements were then imposed, and the levees were rebuilt to conform to these requirements (5 ft of clay with 10^{8} cm/sec permeability or the equivalent). But leachate was discovered again in 1980, indicating that even the improved dikes were not able to prevent seepage.

By contrast, Site B was developed in 1971 with some effort to design ponds that would prevent waste migration. The site was investigated and soil compaction and other design criteria were specified before construction. When the site was investigated in 1978, no seepage was reported, even though the levees did not all conform to the new permeability requirements and had to be modified.

Site A may not have been explicitly sited and designed to prevent waste seepage as Site B was. This possibility appears to have been a significant factor in the performance of the facility with respect to seepage. Building Site A pond levees on a garbage foundation undoubtedly contributed to the seepage problem, and the displacement fill method of improving the dikes apparently was unable to solve the problem. Trench key work apparently did not provide a complete solution either, unless the leachate originated (as the facility owners contended) from an adjacent commercial landfill.

Case Study No. 4

The operating experience at this site illustrates (1) how the materials in the waste can provide an adequate barrier against further waste seepage under certain circumstances, and (2) how liner failure and poor performance can result from deviations in desired liner specifications, reliance on inadequate liner-waste compatibility tests, insufficient attention to geotechnical factors, and poor design and operating practices.

The major surface impoundment systems at this fertilizer manufacturing facility are eleven 14-acre gypsum ponds, an 8-acre evaporation pond, and a 38-acre cooling pond. The gypsum ponds are unlined sedimentation ponds that have been used to recover gypsum for nearly 20 years. The natural buildup and solidification of gypsum in those ponds have rendered them impervious. This fact has been verified by actual examination and permeability testing of the core specimens from the bottom, which have indicated the presence of a very hard material with low permeability.

The FML-lined evaporation and cooling ponds have failed in the past and are currently leaking. The liner specifications, which were written by the facility owner, called for a material that would not deteriorate when exposed to a waste with the following characteristics: pH of 2, maximum temperature of 110°F, 0.5% sulfuric acid, 1.63% phosphoric acid, 0.05% chlorides, 0.5% fluorides, and 1.0% organics. Though the available data indicate that the liner met the alkali and acid (pH 3.0) resistance tests, the material may not have been tested with a waste simulating the above characteristics. The actual liner manufacturer's warranty also provides for an acid resistance of 1% weight change versus an original specification of 0.3% (both at pH 3.0) and limits the definition of organics to only five specific compounds, the total concentration of which is not to exceed 1%. Geotechnical and soil investigations had indicated that the native clay had a high content of calcium carbonate. This soil characteristic (which would lead to gas formation underneath the liner in the event of acidic waste leakage through the liner) was also not addressed in the site and liner design.

Liner bubbles have been observed in the FML-lined ponds. Inspections during repairs suggested seaming failure as the main initial cause of the liner leak. Seepage of the acidic waste into the underlying carbonate-bearing clay resulted in the production of large volumes of gas. Since no provisions had been made for venting, gas accumulation helped spread the seams and further aggravated the leaking. An overload discharge pipe that diverted wastewater from the gypsum ponds to the evaporation pond was also an apparent contributor to the seam failure problem in the splash area. This problem was eliminated by installing a splash pad after the liner area was repaired.

Case Study No. 5

This facility contains eight clay-lined impoundments and demonstrates what can be achieved when the impoundments are well designed, constructed, and operated. The major reasons for the highly successful performance of these clay-lined ponds include: (1) the use of a very impermeable clay (available onsite) as the liner material, (2) the use of competent design, construction, and inspection contractors, (3) a conscientious owner/operator that closely scrutinized all phases of impoundment design, construction, and operation (from site selection to QA inspection), (4) extensive waste-liner permeability studies, (5) excellent QA/QC and recordkeeping during all phases of the project, and (6) good communication (input and feedback) between two different state regulatory agencies and all parties involved in the establishment of the ponds.

The performance of the impoundments is documented by many years of inspection reports and observation of the leak detection systems located beneath each pond. These leak detection systems were field-tested by state inspectors during construction. The good performance of the impoundment is not surprising, since the clay used to line these ponds has held the borate deposits mined at this facility for centuries.

Case Study No. 6

The operating experience at this site illustrates how poor impoundment design and inadequate construction, inspection, and recordkeeping can lead to leakage and poor performance. Wastewaters began seeping laterally out of one impoundment because (1) sand lenses within the natural clay were not identified and removed as specified in the design, and (2) at least one of the embankments was not adequately keyed into unweathered clay to prevent lateral waste migration.

This commercial hazardous waste disposal facility contains three 5-acre SI's lined with in-situ clay (on the bottom) and recompacted clay embankments. Pond 8 received geothermal and petroleum industry sludges and wastewaters, and the other two ponds are currently used for land treatment of organic sludges.

A soils investigation conducted before impoundment design indicated the presence of sand and silt lenses within the natural clay beneath the site. The design specifications called for (1) at least 2 ft of natural clay (with a permeability of 10^{-8} cm/sec) beneath the ponds in which no sand or silt lenses were discovered during pond excavation and construction, and (2) subsequent placement of recompacted clay. The wastes began to migrate laterally along a sand lens underneath the embankment and surfaced outside the impoundment because: (1) not all sand silt lenses were detected by boring tests or during excavation and construction, and (2) at least one embankment of Pond 8 was not keyed into the natural unweathered clay as specified (and this noncompliance with specifications was apparently not discovered and documented during QC inspection).

Though no seepage has been detected outside the other ponds, the other embankments at the site may not have been keyed into unweathered clay. The inspection and engineering certification reports for the site are very poor and unclear on this point.

Case Study No. 7

This facility shows how a combination of good site hydrogeology, proper design and construction, and adequate contingency planning can ensure satisfactory performance for surface impoundments located on in situ clay and diked with compacted clay. The site contains gypsum slury and process wastewaters from a large fertilizer manufacturing operation. Two important site characteristics that contribute to the success of the impoundments here are the very low permeability of the 120-ft-deep, *in situ* clay layer (10^{-8} cm/sec) and the high groundwater table, which provides a reverse gradient and hence an added safety factor against waste exfiltration. Monitoring of the deep groundwater aquifer and more than 9 years of monitoring data from a network of shallow wells have indicated no impacts on groundwater quality and no seepage through sand/silt lenses.

The good performance of the clay-lined ponds can be attributed to the following factors:

- Detailed geotechnical investigation of the site, including extensive laboratory testing of boring samples from subsurface soil.
- Borrow pit excavation within the pond areas that is limited to 5 ft below ground surface and 50 ft from dike bases. The first limitation reduces the possibility of exposing sand/silt lenses, and the second restriction decreases the chance of continuity for any undetected sand/silt lenses.
- Removal of all exposed sand/silt lenses and subsequent compaction of a 3-ft layer of clay over these areas.
- Clay compaction that is done in thin lifts to eliminate voids and meet permeability requirements.
- Comprehensive inspection and testing of pond and dike construction.
- Installation of a network of shallow wells to monitor possible lateral seepage through sand/silt lenses.

During a recent failure of the 100-acre gypsum stack (in the gypsum pond), disaster was averted because of adequate contingency planning and a prepared work crew. When signs of a possible failure were first noticed, ditches that surround the pond were dammed off. Thus when the failure actually occurred, the nearly 6 million gal of acidic water was totally contained. The failure was attributed to long-term consolidation settlement of the underlying soft clay, which caused tension cracking in the overburden gypsum stack and hence failure. The magnitude of the time-dependent settlement of clay and the resistance of the gypsum stack to tension cracking had not been correctly estimated in the original design.

Case Study No. 8

These two large ethylene-propylene diene monomer (EPDM)-lined equalization and retention surface impoundments failed because of excessive swelling and permeation of the liner material and separation of the seams. The waste-liner incompatibility was not predicted by the limited tests preceding liner selection. The selection of EPDM appears to have been based on its low cost, ease of installation, and ready availability. The seam separation problem resulted from deterioration of the glue used and seam laps smaller than those required by the design. Substitution of the clay tiles for perforated PVC pipes in the seepage drainage system caused extensive plugging of the system and loss of capacity. Other factors in the facility's failure were inadequate communication between owner and contractors, inadequate inspection and acceptance procedures, and a less-than-competent project engineer.

The SI's at this facility serve a chemical production plant in an industrial coastal community. Industrial activity has been continuous in the area since about 1900, with changing plant ownership, production, and waste disposal practices. Because extensive onsite disposal has raised the surface elevation 20 to 30 ft above the original, it is nearly impossible to assess SI performance. Monitoring wells indicate the presence of a range of chemicals, some known to be absent from the currently impounded wastes.

Case Study No. 9

This case study underscores the need for nonerosive shoreline protection at the waterline for FML's in large surface impoundments that may experience strong winds and severe winter conditions. Though construction, compaction, and earthwork were thoroughly documented and inspected at this site, liner inspection was limited and undocumented.

This 62-acre uranium tailings pond is lined with 30-mil PVC on the bottom and 30-mil polyester-reinforced Hypalon* on the sides. No form of protective cover was provided for the liner, presumably because of the supposed difficulty of maintaining such cover in the face of strong winds and surface waves. Four documented failures of the liner have occurred in less than 3 years. The first failure occurred 4 months after installation and involved a 300-ft separation of the liner seam caused by deviation from installation specifications. Other failures include numerous punctures and tears resulting from carelessness during installation, a ruptured discharge line, floating debris that was not removed after a winter storm, and wave action against the liner ridge. The leak detection underdrain system failed to detect substantial leaks that occurred at points not directly over the collection pipes.

The experience at this facility illustrates the ineffectiveness of a piecemeal approach to correcting problems that recur because of faulty or inadequate design and construction.

*Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

Conclusions

Conclusions Drawn from the Case Studies

1. Successful facilities must have adequate site investigation, good project planning during design and construction, and rigorous execution of a comprehensive QA/QC program. Problems resulting from inadequate site investigation and poor design and construction cannot be completely corrected through piecemeal remedies applied as the problems surface.

2. The cornerstones of an effective QA/QC program are competent and conscientious supervision and inspection of construction and rigorous documentation and recordkeeping. The QA/QC program should cover all steps of the facility's development—planning, design, construction, etc. The program should also encompass all system elements, support facilities, operations, and corrective measures (monitoring wells, leak detection subdrains, dredging, repairs, etc.).

3. QA/QC programs for facilities lined with FML's should emphasize liner-waste compatibility in liner selection, proper installation procedures (especially seaming), and the use of protective cover (particularly for liners exposed to severe elemental stresses).

4. Unless properly designed, groundwater monitoring programs are not reliable substitutes for subdrain leak detection systems. Groundwater monitoring is more reliable for providing advance warnings of site failures and thereby allowing corrective measures to be taken in time.

5. The successful performance of surface impoundments at two of the facilities was due to (1) a very impermeable clay liner, (2) extensive waste-liner permeability studies, (3) competent design, construction, and inspection contractors, (4) close scrutiny of all phases of design, construction, and QA inspection by the owner/operator, (5) excellent QA/QC and recordkeeping during all project phases, and (6) good communication among all parties involved in establishing the sites.

6. Case studies documenting the performance of hazardous waste facilities can provide the necessary feedback for evaluating various designs and construction techniques and can yield valuable lessons for improving design, construction, monitoring, and operating procedures.

7. The facilities rejected for this study more accurately represent existing SI practices (no engineered site, presence of other pollution source, no data on hydrogeology or site construction, and insufficient monitoring data for performance evaluation).

Conclusions Based on Professional Opinions and the Experience of Experts

1. Siting in suitable geological formations is the best protection and the first line of defense against groundwater contamination, regardless of liner type.

2. In the intragradient design, the facility is intentionally located in the saturated zone and the high groundwater table provides a positive pressure that can prevent migration of leachate or waste in the event of failure.

3. Geotechnical support should be a continuous effort covering not only site investigation and facility design but construction as well.

4. The QA/QC program is essential for guaranteeing the adequancy of

a completed facility. The key elements of the program should be thorough construction inspection, use of competent and conscientious inspectors, and detailed documentation and recordkeeping.

5. The most critical factor in clay liner construction is compaction under proper moisture conditions. Compaction should be aimed at eliminating all air spaces and not necessarily at achieving certain arbitrary Proctor density levels. Compaction wet of optimum is generally sufficient to ensure elimination of air spaces and development of a very impermeable liner.

6. Dessication cracking of clay is highly site- and situation-specific. Since liners are constructed in lifts and there is little chance for alignment of cracks in adjacent lifts, a limited number of shallow cracks not detected during inspection should present no major leakage problem.

7. The critical factors in installing a successful FML are selection of a suitable liner material, use of proper installation procedures, rigorous application of QA/QC, and provision and maintenance of protective cover for the liner.

8. Waste-liner compatibility should be re-examined whenever the character of the waste changes. Compatibility problems can be minimized with good site design and operating practices, pretreatment, and banning of certain wastes.

9. FML installation problems can be minimized by experienced installers, good field supervision and technical assistance to the installer, and minimal field seaming.

10. Protective cover for a liner is essential to prevent damages from the elements, vandalism, pinholes, animals, and chemicals.

11. Use of an FML and a clay liner together provide the advantages of both systems and compensate for the shortcomings of the individual liners.

12. Sporadic plugging of underdrain leachate collection systems remains a problem. No practical measure currently exists to restore hydraulic capacity when a sand and gravel drainage system is plugged.

13. Subdrain leak detectors are superior to monitoring wells and other indirect methods because they permit direct observation, allow more rapid detection of failure, permit monitoring over a relatively large area under the liner, and yield more reliable results. Groundwater monitoring may not provide a true picture of the background conditions and changes in water quality.

Recommendations

A technical manual should be compiled with the considerable accumulated experience in the waste disposal field. The manual should detail how site selection, design, construction, operation, monitoring, maintenance, and repair relate to each other.

The present study should be extended to include additional case studies and experiences of technical experts. The results should be distributed to practicing engineers, owners/operators of hazardous waste management facilities, regulatory agencies, and active researchers.

Specific items that need further study include the following:

- The effectiveness of various FML's
- Seaming methods for FML's
- QA/QC procedures
- Liner-waste compatibility
- The intragradient and hydraulic barrier concepts
- Methods for minimizing and correcting clogging in leachate collection systems
- Methods for obtaining clay permeability data
- Methods for detecting and correcting site failures
- Technical basis and criteria for proper design of groundwater monitoring systems
- Techniques for monitoring the unsaturated (vadose) zone
- Methods for pinpointing liner leaks and repairing them

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The complete report, entitled "Assessment of Hazardous Waste Surface Impoundment Technology: Case Studies and Perspectives of Experts," (Order No. PB 85-117059; Cost: $25.00, subject to change) will be available only from:
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