Observation and Responses to Post-Closure Instances of Localized Instability and Subsidence at the DOE Legacy Management Rocky Flats Site, Colorado—13052

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ABSTRACT

The former Rocky Flats Plant in Colorado began operations as part of the nation's nuclear weapons complex in the early 1950s. By the 1980s the associated heavily industrialized area covered approximately 1.2 km^2 (300 acres) and was surrounded by an approximately 25.3 km^2 (6,245 acre) security buffer zone. The federally owned property and adjacent offsite areas were placed on the CERCLA National Priority List in 1989. To complete closure, all buildings and other structures that composed the Rocky Flats industrial complex were removed from the surface, but remnants remain in the subsurface. Contouring and grading to return the surface to approximate conditions that were present prior to the plant's construction was completed in 2005. A goal of the final land configuration was to provide long-term surface and subsurface land stability. Several instances of localized surface subsidence or instability have occurred since the final configuration. The localized nature and the relatively small areas of observed subsidence and instability indicate that, overall, the final configuration is performing well, but responses to these occurrences and the observations that followed may be useful in planning for the closure and designing the final land configuration and post-closure monitoring at other sites.

INTRODUCTION

The former Rocky Flats Plant in Colorado began operations as part of the nation's nuclear weapons complex in the early 1950s. DOE and its predecessor agencies exercised jurisdiction and control over the facility. By the 1980s the plant's heavily industrialized area covered approximately 1.2 km^2 (300 acres) and was surrounded by an approximately 25.3 km^2 (6,245 acre) security buffer zone that comprised open space with various support facilities and surface water management features. Because plant operations had released hazardous substances to the environment, the federally owned property and adjacent offsite areas were placed on the CERCLA National Priority List (NPL) in 1989. When the nuclear production mission ended in the 1990s, DOE changed the plant's mission to cleanup and closure, and the facility was renamed the Rocky Flats Environmental Technology Site, and subsequently just the Rocky Flats Site.

Cleanup and closure of the Rocky Flats Site was accomplished under CERCLA, RCRA, and the Colorado Hazardous Waste Act (CHWA). The *Rocky Flats Cleanup Agreement*[1] (RFCA) between DOE, EPA, and the Colorado Department of Public Health and Environment (CDPHE) provided the regulatory framework for remedial activities. The activities included decontamination, demolition, and removal of more than 800 buildings and other structures. Although most of these were completely removed, some portions of buildings were left in place 0.9 m (3 ft) or more below the surface grade. Several kilometers of utilities and infrastructure were removed, but portions were also left below the surface grade. What had been an industrial city was turned back into open space.

The physical cleanup was completed in late 2005 following final grading, which was intended to return the site to the approximate surface contours that existed prior to construction of plant facilities and to accommodate storm water and snow melt drainage. The final grading for closure of Rocky Flats is referred to generally as the "final land configuration." One goal of final land configuration was to achieve long-term surface and subsurface land stability. The area reworked to attain this final land configuration comprised more than 1.2 km^2 (300 acres).

Figure 1 is an aerial view of the Rocky Flats Site in 1995, and Figure 2 is an aerial view in 2005.

Figure 1. Aerial view of the Rocky Flats Site, 1995.

Figure 2. Aerial view of the Rocky Flats Site, October, 2005.

Achieving final land configuration included completely removing buildings and surface and subsurface infrastructure in some areas, and leaving portions of buildings and infrastructure in the subsurface in other areas. These subsurface remnants include some building and piping components that contain fixed residual uranium, americium, and plutonium contamination. Asphalt roads and parking lots, storm water management features, such as culverts, storm water outfalls, and drainage ditches, were removed, and five functional channels (referred to as FC-1 through FC-5) were constructed to convey storm water to North and South Walnut Creeks. Former building footer drains and other subsurface infrastructure such as storm water and sanitary sewer lines, process waste lines, and utility lines were removed or disrupted and grouted where feasible to eliminate preferential groundwater flow paths.

The final CERCLA/RCRA/CHWA response actions were approved in the *Corrective Action Decision/Record of Decision for Rocky Flats Plant (USDOE) Peripheral Operable Unit and the Central Operable Unit*[2] (CAD/ROD) after the completion of cleanup actions under RFCA and final land configuration. Grading of areas where remnants of former buildings were left in the subsurface and of landfills that were closed in place was evaluated and approved under RFCA. Final surface contouring and construction of functional channels was conducted to be consistent with actions approved under RFCA but was outside the scope of the RFCA regulatory process.

The response actions selected for the Central Operable Unit (OU), which contains the former industrial area, are institutional controls, physical controls, and continued monitoring and maintenance. For practical future land management, the boundary for the Central OU was drawn to form a single parcel to include all areas that required a continuing response action. The remaining Rocky Flats Site area comprises the Peripheral OU, which does not require any response action[1]. The 5.29 km^2 (1,308 acre) Central OU includes areas with portions of demolished buildings deeper than 0.9 m (3 ft) below grade, subsurface utility infrastructure remnants, areas with residual surface and subsurface soil contamination, areas with groundwater contamination and groundwater treatment systems, several disposal pits and trenches, and two closed landfills. The *Rocky Flats Legacy Management Agreement*[3] (RFLMA) between DOE, CDPHE, and EPA replaced and superseded RFCA. RFLMA provides the regulatory framework for implementing the final response action in the Central OU.

As required by RFLMA, inspections and monitoring of the Central OU areas containing subsurface remnants and engineered components are conducted so that any observed subsidence or instability can be addressed in a timely manner. These actions help to ensure that such conditions will not present a significant subsurface contamination exposure pathway or disrupt the performance of a remedy component, so that the remedy remains protective of human health and the environment. Routine inspections also serve to identify conditions that may present a hazard to workers or to wildlife.

[1] The Peripheral OU was deleted from the CERCLA NPL in 2007[4, 5], and jurisdiction and control of most of the Peripheral OU land was transferred to the U.S. Fish and Wildlife Service to establish the Rocky Flats National Wildlife Refuge. DOE manages the Central OU to be compatible with the surrounding wildlife refuge use, but if necessary, remedy implementation requirements take precedence.

OBSERVED CONDITIONS AND RESPONSES

Several instances of localized surface subsidence or instability have occurred in the Central OU since completion of the final land configuration, including the following:

- Subsidence and settling in the immediate area of a stairwell for former Building 881 and a possible similar occurrence at former Building 771.
- Slope surface instability and the expression of groundwater seeps at the closed Original Landfill.
- Subsidence of a steep, constructed hillside south of former Building 991 and FC-4 related to intentional disruption of a French drain during closure.

Figure 3 is a map of the remnants of buildings and process waste lines that remain in the Central OU subsurface, and the location of the closed Original Landfill. The outlines of former buildings or structures removed and the locations of the five FCs are also shown on Figure 3.

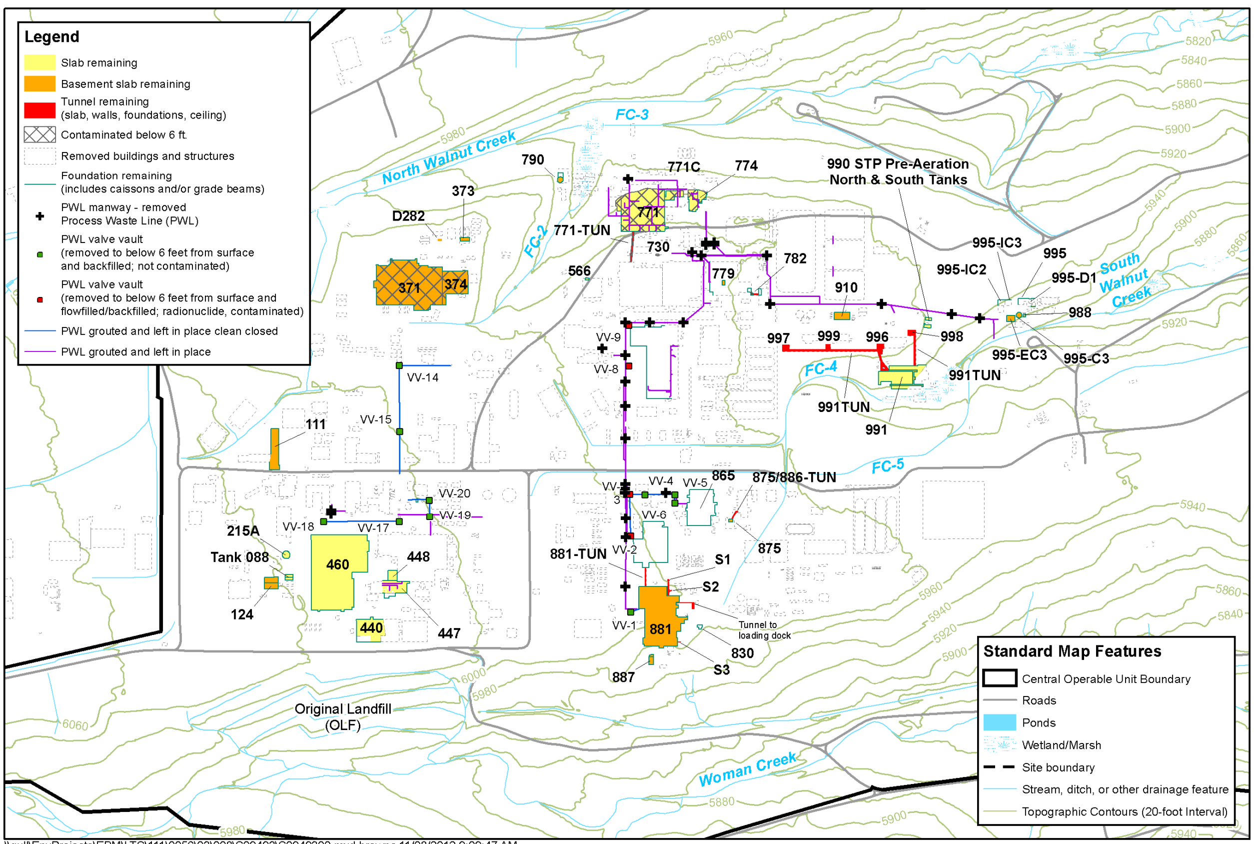

Figure 3. Subsurface Features.

DOE responded to the observed conditions by investigating probable causes, making repairs or changes to the areas involved, and instituting localized administrative access controls and more frequent inspections as needed. The relatively small areas of observed subsidence and instability indicate that, overall, the final land configuration is performing well. However, these observed conditions and responses may be useful in closure planning and designing the final land configuration at other sites.

Former Building 881

An annual inspection and monitoring of evidence of significant erosion and violation of institutional controls in the Central OU is conducted as required by RFLMA. During the annual inspection conducted on March 15, 2011, a deep hole (approximately 1.8–2.4 m (6–8 ft) in diameter; actual depth unknown).was found near the southwest corner of former Building 881 (881 hole) (see Figure 3). Figure 4 is a photograph of the observed hole.

Prior to this inspection, and during monitoring and surveillance of the Central OU throughout the year, several locations had been observed in the vicinity of buried building remnants with small depressions or holes that were minor (15 to 30 cm [1 to 2 ft] deep) and very limited in area (0.3 to 1.5 m [1 to 5 ft] in diameter). These areas are addressed by filling with soil and periodically monitoring the filled area. On occasion, the added soil settles further, and more soil needs to be added over the next year or two to bring the elevation to that of the surrounding ground surface. This typically appears to be sufficient to prevent further depression or hole formation.

Figure 4. 881 hole observed in 2011

The 881 hole was not present in inspections prior to 2011 and was significantly larger and deeper than other observed depressions and holes in the vicinity of buried building remnants. The area was fenced off temporarily while the evaluation of the exact location, approximate size, and approach to filling the hole was completed. Because of safety concerns related to working close to the hole to take precise depth measurements and visually observe the deeper reaches of the hole, determining the possible cause of the hole and the planning to fill the hole were based on conclusions drawn from documentation of the demolition of the building.

Building 881, like several other buildings at Rocky Flats, was constructed into the hillside. The west, north, and most of the east walls of the building were mostly underground, and the roof was approximately the same elevation as the grade of the northwest corner. It had two main floors with a partial basement level consisting of tunnels below the first floor. The first floor included loading dock areas accessible on the south and southeast building walls.

According to the final characterization surveys of Building 881 after decontamination and removal of equipment, the building was free of radiological and other hazardous material and met release criteria. After demolition and removal of various structural components and backfilling of the basement and selected first floor areas, it was demolished by explosives. This resulted in the roof and second floor collapsing onto the first floor (i.e., above the basement level). The area above the collapsed floors was then filled with soil, contoured, and revegetated consistent with the final land configuration design. This work was completed in late 2004.

The approximate location of the observed hole was determined using a hand-held Global Positioning System (GPS) unit. A comparison of the GPS coordinates to survey coordinates for the building location indicated that the hole was near the southwest corner of the former building.

Prior to demolition of Building 881, a stairwell was located on the southwest side of the building leading to the basement level near the loading dock area. Rebar and what appear to be metal railings are evident in Figure 4. The hole appears to be due to settling of fill material into an area at the bottom area of the staircase that did not fully collapse during explosive demolition, creating voids.

Figure 5 is a copy of the building first floor footprint taken from the Building 881 Pre-Demolition Survey Report[6] showing the stairwell location. Figure 6 is a photograph of Building 881 showing the western wall of the building after explosive demolition and before backfilling. A photograph of the wall looking east could not be located in the archives, but the general location of the stairwell is thought to be behind the standing wall as indicated on the Figure 6 photograph.

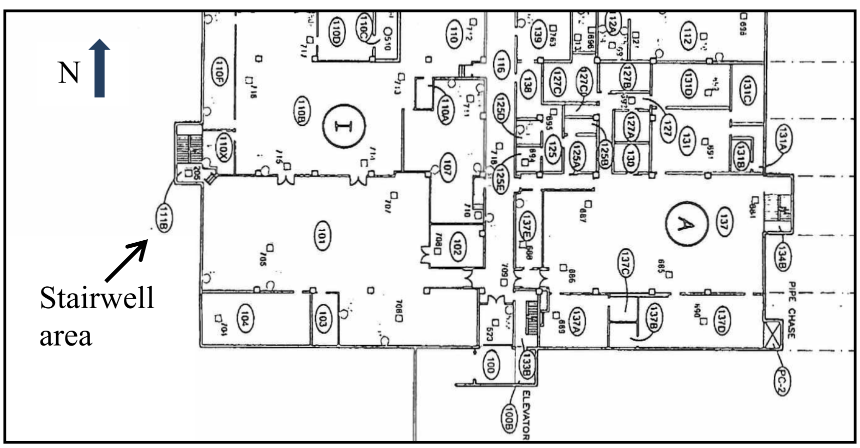

Figure 5. Stairwell shown on first floor layout drawing. Stairwell leads from second floor to basement level below first floor.

The general area surrounding the hole was fenced off with temporary fencing, and the hole was filled on March 30, 2011, with 25.4 metric tons (28 tons) of structural fines and 18 metric tons

(20 tons) of Rocky Flats Alluvium. Fill material was hauled to the site and staged approximately 18 m (60 ft) away from the hole. An excavator was then used to move the material from the staging area directly into the hole. Fill material was mechanically compacted using the bucket of the excavator. Final grade of the compacted fill was left approximately 30 cm (1 ft) above the surrounding grade to allow for further settling.

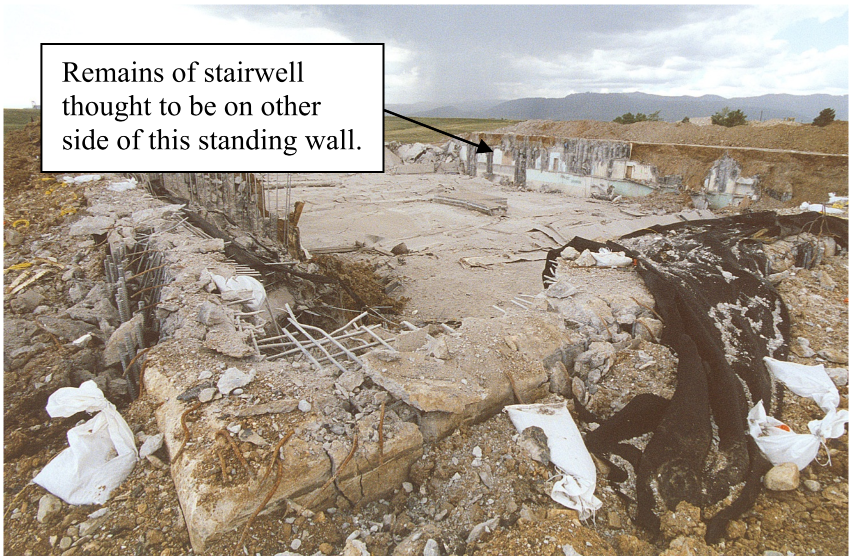

Figure 6. Building 881 after explosive demolition, before backfilling (looking southwest).

Figure 7. Backfilling the 881 hole in 2011 (excavator provides comparison for the hole size).

Based on the depth of the 881 hole and the possible safety hazard from holes that could form above subsurface building basements and tunnels that had been filled, site operations personnel now inspect these areas quarterly. The surface locations coinciding with these subsurface locations have also been marked with fence posts to assist surface observation. These areas are associated with former buildings 371, 771, 881, and 991 (see Figure 3).

By the 2012 annual inspection, conducted March 13, 2012, a small hole had formed in the area that was filled in 2011, which is consistent with observations at other holes that have been filled. Figure 8 is the hole observed during the 2012 inspection. This small hole was filled, and periodic inspection of conditions is continuing.

Figure 8. 881 hole approximately 1 year after backfilling.

Former Building 771

Beginning in late 2011, a noticeable depression formed in the gravel road that runs generally south of the buried remnants of Building 771. This building consisted of two stories constructed into a north-facing hillside, with the south and east walls buried into the hillside. Building 771 was mechanically demolished with most of the south and east walls, the first floor, and a portion of the second floor backfilled in place after removal of all equipment, dismantlement of interior walls, and completion of decontamination to the extent feasible. The remaining building components are deeper than 1.8 m (6 ft) below the final surface elevation. Some portions of the remaining concrete have fixed radionuclide contamination above free-release limits.

The approximate location of the observed hole was determined using a hand-held GPS. A comparison of the GPS coordinates to survey coordinates for the building location indicated that the hole was near the southeast corner of the remaining buried portions of the south and east walls of Building 771 (see Figure 3). In December 2011 this portion of the gravel road was cordoned off, and a temporary pathway for vehicle use was demarcated about 6 m (20 ft) to the south while the depression was being evaluated.

The southeast corner area of Building 771 is the location of the building exhaust stack tunnel that was left in place and backfilled. This location also had a stairwell on the first floor, and the stairwell is believed to have been left in place. Figure 9 is a copy of sections of the building's first and second floor footprints taken from the Building 771 Decommissioning Closeout Report[10] and showing the stairwell and stack tunnel locations. No photographs of this area of the wall and tunnel could be found in the archives.

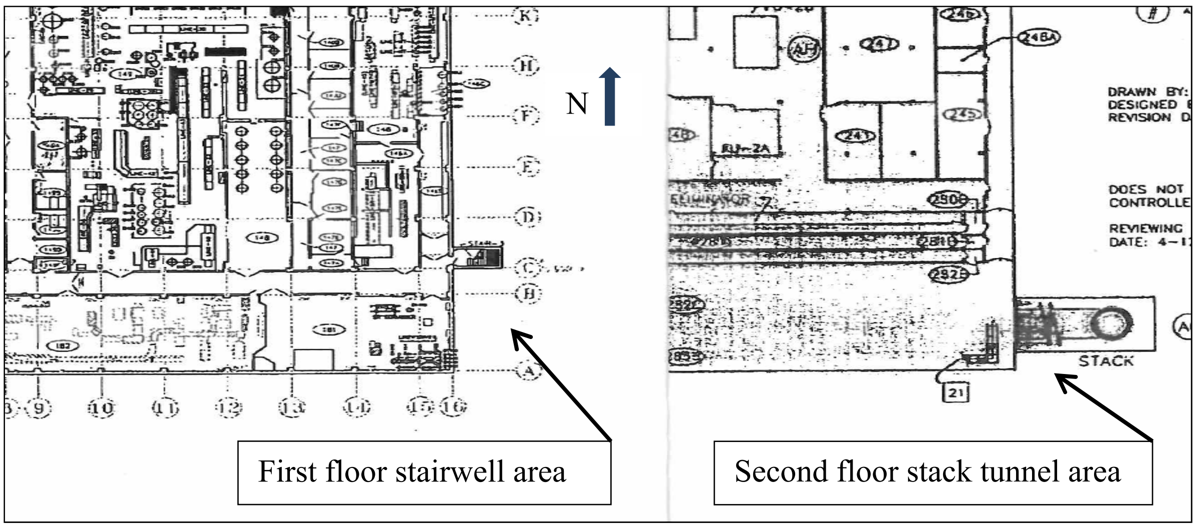

Figure 9. Building 771 stairwell and stack tunnel locations.

Figure 10 is a photograph of the cracks that formed in the road in early 2012. Since the general location of this depression and cracking has characteristics similar to those of the 881 hole and appears to correlate to subsurface building remnants, the gravel road was permanently relocated to the south, and the depression area and road was filled, graded, and revegetated in May 2012. Periodic inspection of conditions is continuing.

Figure 10. Depression and cracking in gravel road south of Building 771.

Original Landfill

The Original Landfill (see Figure 3) was used to dispose of Rocky Flats solid sanitary and construction debris wastes from 1952 to 1968. Under the final interim measure/interim remedial action for the Original Landfill[7] approved under RFCA, the landfill was closed with a 0.6 m (2 ft) thick soil cover. Construction was completed in 2005. The *Original Landfill Monitoring and Maintenance Plan*[8] (M&M Plan) was approved prior to the CAD/ROD. The CAD/ROD incorporated the M&M Plan as a component of the final response action.

The landfill was not designed or operated as an engineered landfill and was not considered a RCRA- or CHWA-regulated hazardous waste disposal facility. Waste was merely dumped in the area vertically below and just south of the southern edge of the alluvial pediment on which the former industrial area was located.

To enhance slope stability, the existing slopes were regraded before the soil cover was placed, and a buttress fill was installed at the toe of the landfill. The buttress includes a gravel drainage layer designed to collect groundwater associated with historical seeps prevalent in some locations along the hillside and direct it into the alluvium south of the landfill adjacent to Woman Creek. The groundwater was anticipated to percolate through the landfill subsurface, while precipitation runoff would be managed by perimeter drainage channels and seven diversion berms with a cumulative length of more than 1.6 km (1 mile) on the cover. These surface water run-on and runoff control features direct flow toward the perimeter channels.

Beginning in 2007, localized slumping and settling of the soil cover and intermittent seeps expressing on the cover surface were observed during required monthly inspections. Surface cracking and differential settling, which provided a preferential path for precipitation below the cover, was most noticeable near the western perimeter channel. Figure 11 is a photograph of the cracking observed in 2007.

Figure 11. Cracking along downgradient side of the Original Landfill diversion berm.

In addition, field measurements showed that significant portions of the diversion berms no longer met the minimum M&M Plan–specified 0.6 m (2 ft) height. DOE notified CDPHE and EPA of the observed conditions, and the parties consulted regarding appropriate actions to address them. DOE continued monitoring berm conditions and made minor repairs as specified by the M&M Plan, adding and compacting soil to localized areas to maintain berm and cover integrity.

A geotechnical investigation was conducted to determine the possible causes of the observed localized slumping and settling and to develop feasible mitigation alternatives. The investigation also considered the possible impacts of the seeps and the maintenance of berm heights and channel slopes to ensure adequate water run-on and runoff controls.

The geotechnical investigation fieldwork was conducted between December 2007 and April 2008. Eight test pits, approximately 6 m (20 ft) long and 3.4 to 4 m (11 to 13 ft) deep, and a ninth test pit, approximately 6 m (20 ft) long and 0.9 m (3 ft) deep, were excavated. Seven boreholes, approximately 8.5 to 11.9 m (28 to 39 ft) deep (into bedrock), were drilled using sonic drilling technology to obtain continuous core samples and to install inclinometers to accurately measure future movement. Throughout the work, a geologist made field observations, and laboratory analyses were conducted to determine mechanical properties of the test pit and borehole samples.

A geotechnical investigation report[9] concluded that an organic-rich clay layer at or near the bedrock contact appears to be a weak interface area. Modeling predicts small-scale instability due to percolating moisture that lubricates this weak interval. The Original Landfill buttress is providing stability as intended, and there is no large-scale instability predicted; therefore, the observed conditions did not appear to indicate a need for urgent or major responses.

The investigation also concluded that maintenance of the cover to minimize percolation would reduce the amount of moisture that could lubricate the weak interval, but groundwater would continue to be a source of moisture. The historical seeps also did not present a significant concern because they did not contribute to cover erosion, and the water could be directed to the perimeter channels via the diversion berm channels.

Modifications to certain features were recommended, and the construction to complete the necessary repairs and to implement design changes was completed in November 2008. These steps included changes to the minimum diversion berm height, regrading and inclinometer monitoring.

Minimum diversion berm heights were originally based on the drainage area served by the entire berm length. To simplify monitoring and inspection, the calculated minimum berm height for each berm was originally adjusted up to a 0.6 m (2 ft) minimum uniform height, even if this height was unnecessary (i.e., excessive).

Rocky Flats Alluvium used to construct the berms proved to be prone to slumping. Regrading and filling the berm structures back to a 0.6 m (2 ft) minimum height would require heavy equipment and significant amounts of fill material and erosion controls, and would destroy established vegetation. A lower-impact approach was selected. New subdrainage areas, based on 61 m (200 ft) lengths along each berm, were used to calculate the minimum height required for each subdrainage area berm to convey a 1,000-year, 24-hour precipitation event. This provides freeboard capacity to convey the 100-year, 24-hour event, which is a design criterion for the berms.

Approximately 24 percent of the total berm lengths had minor amounts of Rocky Flats Alluvium added at the top using light construction equipment to meet this new minimum height in September and November 2008. Inspections in subsequent years have resulted in the need to add soil to a progressively smaller percentage of berms to maintain the minimum heights. Erosion control matting is installed over the added soil, and the areas are reseeded.

The west perimeter channel was recontoured by cutting and filling to lessen the grade of the side slope, add backfill where the channel was excessively deep, and improve stability of the adjacent hillside. An existing subsurface gravel drain at the southern end of the channel was extended and tied into an existing subsurface gravel drain at the north end of the channel to help manage seepage in this area.

Movement of the seven inclinometers has been monitored approximately monthly since installation. Inclinometers deflect according to lateral movement of the ground in which the inclinometer is located. The inclinometers located on the west side of the landfill had noticeable monthly incremental deflection totaling several centimeters between approximately early 2009 and the end of 2010, and some surface cracking was noted. For the last 2 years, the inclinometers show no or only slight deflection, and only very minor surface cracking has occurred. Based on this monitoring, the regrading, repairs, and maintenance actions implemented for the Original Landfill appear to be effective.

Hillside Subsidence

During expansion and development of the high-security, protected area within the former industrial area in the late 1970s to early 1980s, a valley south of Building 991 was filled with up to 9.1 m (30 ft) of fill to provide a uniform surface that would be easier to monitor for security purposes. A French drain was installed at the base of the fill to stabilize the artificial hillside that was constructed in the former valley, and the drain was equipped with an outfall. As a part of final land configuration, it was necessary to address this outfall, as water containing low levels of contaminants flowed directly from it into the planned FC-4 wetland. Based on consultation among the RFCA parties, in 2005 the outfall portion of the drain was excavated and removed, and the east-west portion of the drain was interrupted and backfilled with grout. The hillside was regraded and onitoring well 45605 was installed immediately downgradient (north) of the east-west drain and upgradient (west) of the point at which that drain had been interrupted.

Slumping on the hillside was first apparent in early January 2006, when small cracks were observed across the surface of the backfilled excavation. These cracks broadened, extended, and multiplied throughout 2006, accompanied by increasing horizontal and vertical displacement and severe protrusion and kinking of the well 45605 casing.

Observations of the developing slumping indicated that the removal of the French drain outfall had allowed collected groundwater to saturate the hillside, causing it to destabilize. The hillside cracking presented a potential worker hazard due to the depth and width of the cracks and unstable ground. The area was delineated with warning rope, and access to the area and to well 45605 was administratively controlled to prevent injuries. Because the hillside slumping was not in an area with buried building or infrastructure remnants, the RFLMA parties agreed to allow the slump to continue to develop to a point at which movement slowed significantly or stopped on its own. Regrading to repair the subsidence and stabilize the hillside was also prioritized based on when well 45605 needed to be repaired or replaced, to allow safe sampling of the groundwater monitored by this well.

Figure 12 shows the condition of the slump and well 45605 in 2007, shortly before construction work to address the slump and to replace the well began.

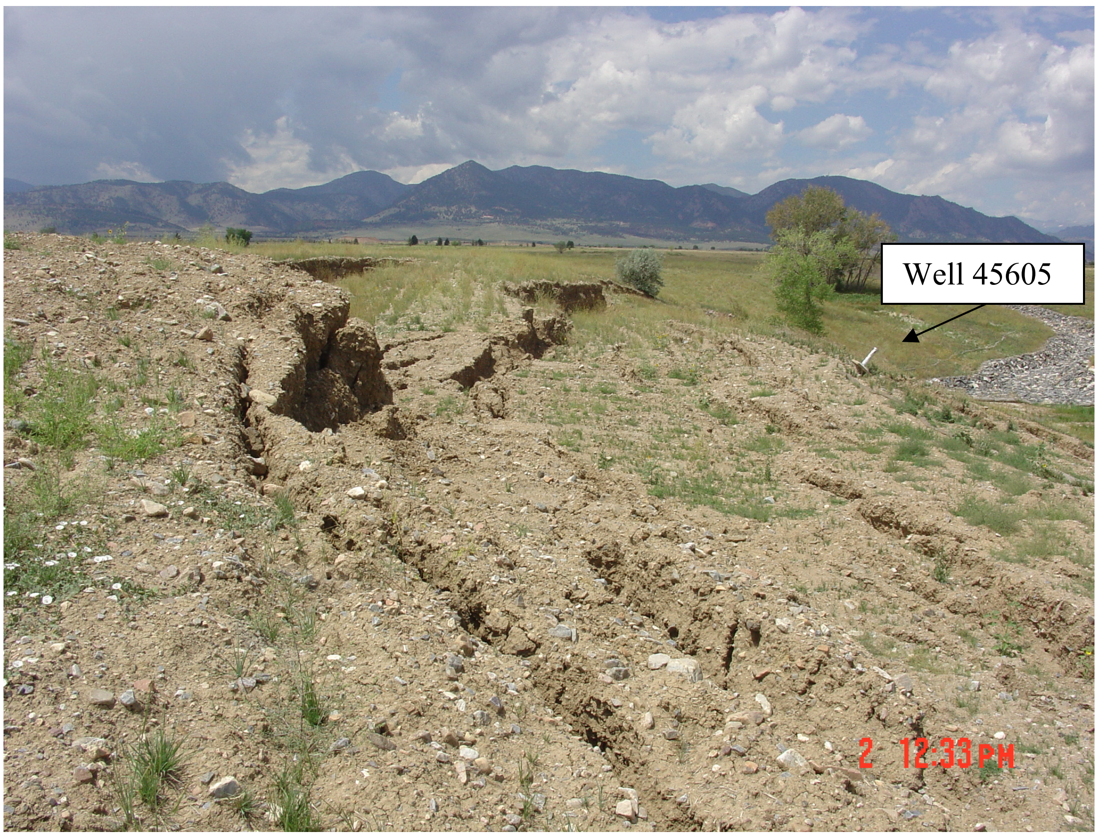

Figure 12. Hillside slump and cracking.

The stabilization regrading was designed to remove about 5,350 m^3 (7,000 yd^3) of the fill material and return the hillside to a closer approximation of the hillside topography that existed prior to filling of the valley area. No adjustment to the abandoned French drain was made, because the original goal of promoting wetland formation in FC-4 was being met.

Well 45605 was abandoned, and as soon as the hillside was recontoured, the well was replaced. Soils that were removed during this 2008 regrading work were hauled to an area just south of the project area, where the former 903 Pad had been located. This material was spread to provide approximately 3o cm (1 ft) of soil over what had mostly been poorly vegetated road base. The regraded hillside and the soils placed at the former 903 Pad area were successfully revegetated with native grasses.

The regrading was largely successful in stopping the slumping and mitigating the conditions that presented safety concerns due to hillside cracking and movement on the hillside. Some distinct but relatively minor differential settling along the top of the hillside occurred in the first couple of years after the regrading, but these do not appear to be propagating further. The replacement well casing shows signs of minor movement, but the well remains serviceable. Periodic inspections of the hillside condition are conducted, and at present, no additional actions are planned.

DISCUSSION

The examples of localized surface subsidence or instability that have occurred in the Central OU since the completion of the final land configuration required varying degrees of site staff time to evaluate and to plan and implement appropriate actions in a timely manner. Evaluations were often helped by having staff who had been involved in the cleanup and closure activities available to assist. Staff with an institutional knowledge of the history of the areas of concern and related sources of information that might be readily available also makes conducting evaluations easier.

Even though these examples did not present immediate remedy performance or uncontrollable safety concerns, they required efforts over and above the routine post-closure monitoring and maintenance activities. In some instances, significant engineering resources were also needed to develop construction designs and statements of work. Procurement for appropriate construction and geotechnical engineering services takes time, and oversight of the subcontracted services also takes significant staff time.

Consultation with regulatory agencies, obtaining approvals as required, informing stakeholders and reporting, follow-up inspections, and additional monitoring also may require significant effort and time to complete. The RFLMA party consultative process continues to prove extremely beneficial in developing and implementing appropriate courses of action in these situations.

CONCLUSIONS

Experience in evaluating the causes of the observed conditions and in implementing appropriate responses provides some lessons learned to consider in the transition from planning and implementing site closure to providing post-closure care. Each of the instances of instability discussed above might have been avoided with additional attention to potential longer-term consequences of closure designs and methods. Compacting backfill in building remnants presents special difficulties, particularly if the structure is demolished by explosion, due to the resulting presence of void spaces. Smoothing a hummocky hillside that features active seeps and signs of historical slumping does not preclude continuation of those conditions and behaviors, even if a buttress and seep drainage features are included in the final design. Finally, removal of engineered subsurface drains can lead to unintended consequences when the drains are no longer present to provide their stabilizing function.

To improve post-closure success and reduce unanticipated costs, the closure and post-closure teams should implement several measures. These include (1) preserving and making information on remaining physical conditions readily available to the post-closure team, (2) including persons with a working knowledge of the cleanup and closure work on the post-closure team, and (3) planning for a wide range of support that might be needed to address situations that are different from routine monitoring and maintenance involved in remedy implementation, including engineering, procurement, and construction oversight.

Considering and mitigating possible post-closure conditions can be costly to a closure project. However, thorough consideration of the possibilities is warranted, and it may be prudent and cost-effective to address those that may be deemed more likely by revising the closure design. The costs to implement adjustments in design and construction during site closure, when manpower, infrastructure, and construction equipment are readily available, are typically much lower than if the work must be performed after closure by a very small staff.

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