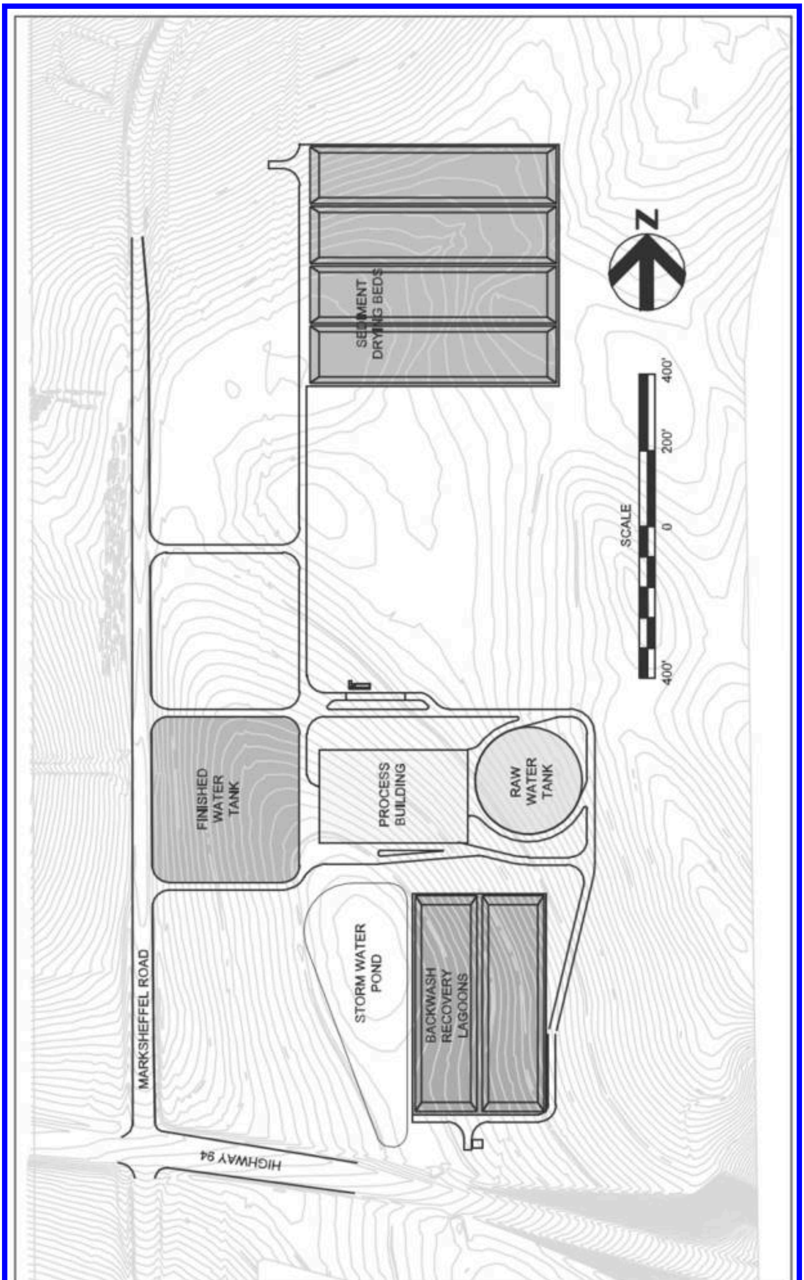
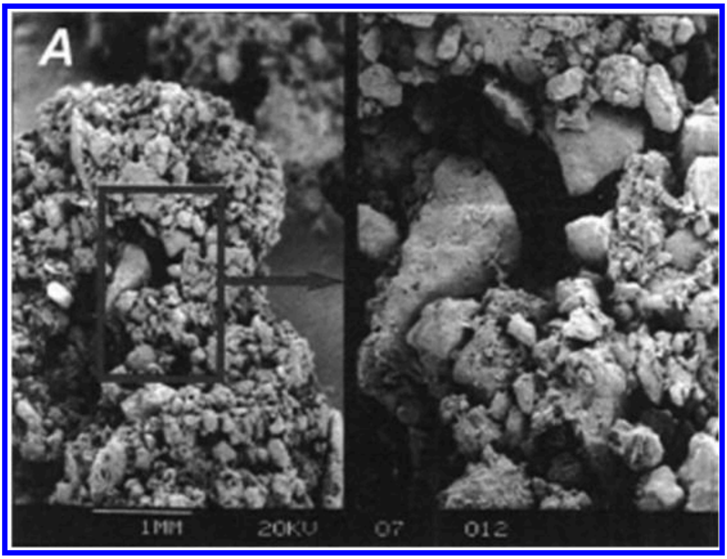


FIG. 3. Site Plan showing the proposed major structures (Image Source: Carollo Engineers)



Photograph 1. Microscopic image of collapsible soil (Image Source: White 2008)

Photograph 2. Photographs of damaged structures resulting from collapsible soils (Image Source: White 2008)

PROJECT CHARACTERISTICS

The SDS project is being developed by Colorado Springs Utilities (CSU) to meet its service area demands for approximately the next 50 years. The SDS project consists of multiple components to convey, store, and treat raw water for the cities of Colorado Springs, Fountain, and Security. One of the key components of SDS project is the WTP.

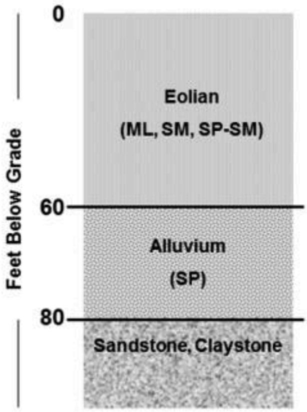
The WTP site is approximately 489,670 m^2 (121 acres) and is located at the northeast corner of the intersection of Highway 94 and Marksheffel Road in Sections 4, 9, and 16, T14S, R65W. The site location is identified on Figs. 1 and 2. The WTP site was formerly used for ranching. Topographical relief at the site is about 40 ft with the highest elevation (El.), about 1935.2 m (6349 ft), near the eastern edge, approximately 335.3 m (1,100 ft) north of Highway 94 and the lowest area, near El. 1923 m (6309 ft), in the southern "low area." Based on topographic contours, the site generally drains from north to south, along the west side of the site and eventually discharges from the site through a culvert under Highway 94.

The current long-term plan for the WTP includes an ultimate plant configuration of three parallel, separately designed and constructed treatment trains. The first train will have a treatment capacity of about 189,300 m^3/d (50-mgd). The ultimate WTP capacity will be about 681,374 m^3/d (180 mgd). The current construction project includes a Process Building, a Raw Water Tank, a Finished Water Tank and Pump Station, a Backwash Recovery Lagoon, Sediment Drying Beds, a Stormwater Pond, and a Decant Pump Station.

GEOTECHNICAL INVESTIGATION

The RJH investigation included 13 geotechnical borings, which were drilled with hollow-stem augers and Standard Penetration Test (SPT, ASTM D1586) sampling. RJH also performed nine Cone Penetrometer Tests with a 266.9 kN (30-ton) truck-mounted cone rig in general accordance with ASTM D 5778. Tip resistance, sleeve resistance, and pore pressure were measured electronically as the 35.7 mm (1.4 in) diameter cone was advanced. Brierley performed 32 additional SPT borings to further define the nature and variable thickness of the collapsible soils. Additionally, thin-walled 76.2 mm (3 in) diameter relatively-undisturbed Shelby tube samples were successfully obtained within the eolian soils to reduce the potential for disturbance to the soil matrix, thus enabling higher-quality laboratory tests.

The borings indicate that subsurface materials generally consist of 8.5 m (28 ft) to 18.3 m (60 ft) of eolian soils. The eolian soils are underlain by dense, coarse alluvium, which was measured to be at least 6.7 m (22 ft) thick in areas. The alluvium is underlain by claystone, siltstone, and sandstone of the Dawson Formation. A generalized soil profile is shown on Fig. 4 and a geologic profile through the treatment train area (not including bedrock) is shown on Fig. 5.



Structure	Eolian Thickness (ft)
Raw Water Tank	60
Process Building	40
Finished Water Tank	40
Sediment Drying Beds	40
Backwash Recovery Lagoons	50

FIG 4. Generalized soil profile created from geotechnical borings and the anticipated eolian thickness beneath proposed structures

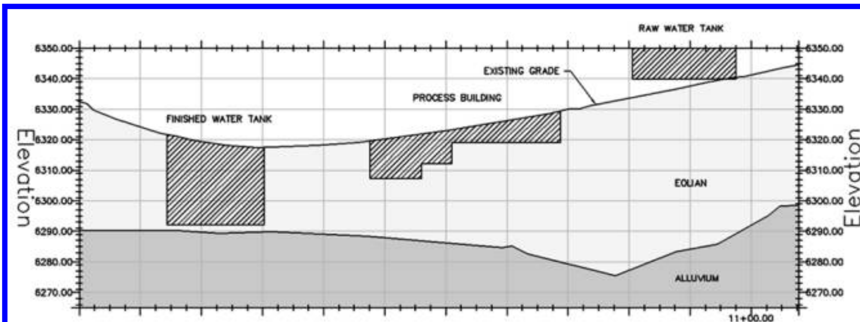


FIG. 5. Geological profile through the treatment train

Laboratory classifications (ASTM D2487) of the eolian soils deposit ranged from silt (ML) to poorly-graded sand with silt (SP-SM) with the majority of the samples classifying as silty sand (SM). Fines (minus No. 200 sieve) contents ranged from 7 percent to 51 percent and liquid limits ranged from 23 to 25. Samples showed a collapse potential (ASTM D4546) of 0.5 percent to 6.8 percent when inundated under a seating load of 47.9 kN/m^2 (1,000 lb/ft^2).

ALTERNATIVES ANALYSIS

Brierley determined that if the WTP structures were built directly on the eolian soils, settlements of up to 279.4 mm (11 in) could occur due to the collapse potential. Potential settlements of this magnitude were clearly unacceptable. Mitigation techniques, including full-depth over-excavation and replacement with compaction, pre-wetting and surcharging the site, stone columns, and deep dynamic compaction

(DDC), were considered by Brierley and the design-build team. These methods are shown in Fig. 6.

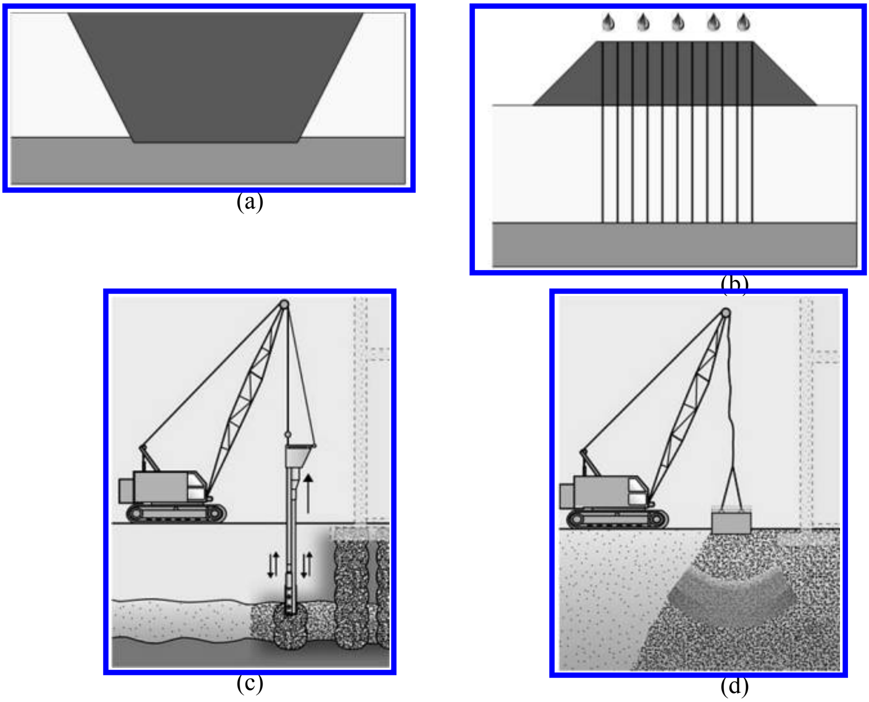


FIG. 6. Illustration of techniques used to mitigate collapse potential of eolian soils: (a) Over-excavation, replacement, and recompaction; (b) Pre-wet with wells and surcharge; (c) Stone columns (Image Source: Hayward Baker); and (d) Deep dynamic compaction (Image Source: Hayward Baker).

Pre-wetting with drains and surcharging was considered from the fundamental point of view that, if the soils were subjected to wetting via closely-spaced gravity standpipe wells and a surcharge similar to the anticipated structure loads was applied, that the collapse would be induced prior to construction, thus rendering a suitable subgrade. This method was not pursued because the amount of water needed would be tremendous and the project team did not consider this to be a tried and proven technique. The authors later realized that a method similar to this had been employed by the Bureau of Reclamation at Pueblo Dam where a 9.1 m (30 ft) thickness of similar soils was treated along a portion of the dam embankment foundation.

Stone columns are installed with large vibratory probes that penetrate into a soil deposit and introduce compacted aggregate material, which form a column of densely compacted soil as the vibratory probe is progressively raised to the ground surface.

The stone columns are installed in a grid pattern at regularly spaced intervals that reinforce and densify a zone of soil. Stone columns have the advantage of transferring structure loads to lower strata. Due to the large number of stone columns that would be required and the significant depth to deeper stable strata, stone columns were considered to be too expensive for the project.

DDC consists of repetitious free-drops of a 88.9 kN (10-ton) to 266.9 kN (30-ton) weight from a height of 15.2 m (50 ft) to 21.3 m (70 ft) (Photograph 3). This puts enormous energy into the ground and in the right soil conditions it can improve soil density for tens of feet in depth. DDC is commonly used for loose, granular soils, for old construction debris fills, and other urban "junk" fills. The application of DDC to collapsible soils is not well documented in the literature; however, a few case histories were identified. Because the eolian soils deposit is essentially loose sand cemented at the grain to grain contacts, it was reasoned that if the compactive energy from the falling weight was enough to break these bonds, then the DDC concept would be effective.


(a)


(b)

Photograph 3. Photographs of DDC equipment: (a) Crane with a 21-m height boom; and (b) 14.5-metric ton weight.

DDC was considered a viable option for subgrade improvement beneath the concrete-lined lagoon structures (sediment drying beds and backwash recovery lagoons). These structures are not as critical or as sensitive to differential settlement as the main treatment train structures. Therefore, DDC was pursued further for the lagoons and over-excavation, replacement, and recompaction was used for the main treatment train structures (Photograph 4).

Photograph 4. Aerial photograph of the main treatment train area (Source: Colorado Springs Utilities, August 2013)

DEEP DYNAMIC COMPACTION

Because the lagoons are lightly loaded structures, Brierley determined that the depth of over-excavation at the lagoons could be limited to 6.1 m (20 ft). It was further considered that if DDC was effective to a depth of about 6.1 m (20 ft), it could be applied in lieu of over-excavation. However, because DDC has not been used on Colorado's collapsible wind-blown sands, Brierley recommended that the owner and the contractor conduct a pilot test to demonstrate its effectiveness. Because of the potential for significant cost saving, a pilot test was performed.

The design-build team assembled a RFP package, which outlined locations of test plots and desired outcomes in the two areas of lagoon structures. The RFP required SPT borings and laboratory testing to be performed both before and after the DDC trials. Before and after ground surveys were also required. The grid pattern spacing was varied so that an optimized foundation treatment approach could be developed. The design-build team interviewed two specialty DDC contractors and chose Densification, Inc. to perform the pilot test, which included the anticipated DDC equipment.

The pilot test was completed in May 2013 and resulted in an average increase in SPT N-value of more than 5 blows per 30.5 cm (1 ft) (N) over roughly the upper 6.1 m (20 ft) of the eolian soils deposit and average surface settlements greater than 6 in, as determined by comparing the before and after ground surface elevations. The pilot test was deemed a success and full production DDC work began in July 2013.

The pilot test and the production DDC work utilized a 142.3 kN (16-ton) weight dropped from a height of 21.3 m (70 ft). The weight was dropped seven times per point on a 4.6 m (15 ft) by 4.6 m (15 ft) offset grid pattern as shown in Fig. 7. A total of 1,989 drops was performed for the Backwash Recovery Lagoons and 3,916 drops for the Sediment Drying Beds. The DDC work created craters, which were typically 2.7 m (9 ft) in diameter and 0.3 m (3 ft) to 1.2 m (4 ft) deep (Photograph 5). On average, soil density as inferred from the SPT tests improved by an average N-value of 6 bpf over an improvement depth of 5.5 m (18 ft) to 7.3 m (24 ft) (Fig. 8). Soil samples collected during SPT tests indicated an average increase in dry unit weight of 80.1 kg/m^3 (5 lb/ft^3) over an improvement depth of 4.6 m (15 ft) to 7.3 m (24 ft) (Fig. 9). Ground surface settlements, as measured by before and after ground surveys, ranged from 177.8 mm (7 in) to 215.9 mm (8.5 in).

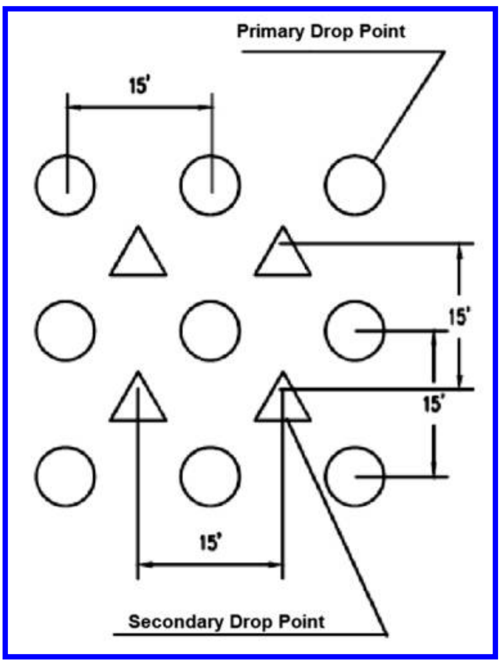
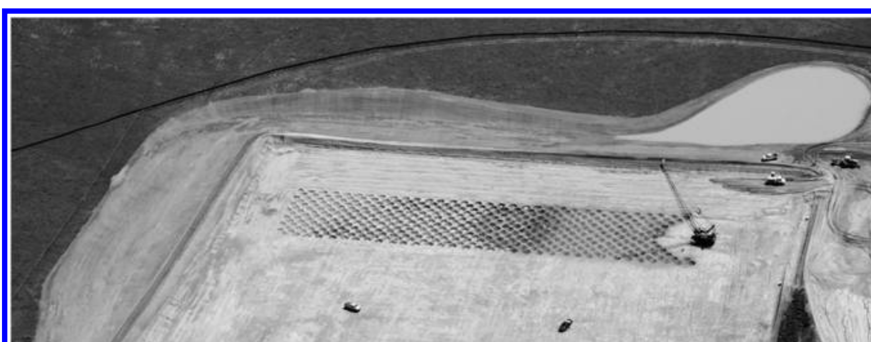


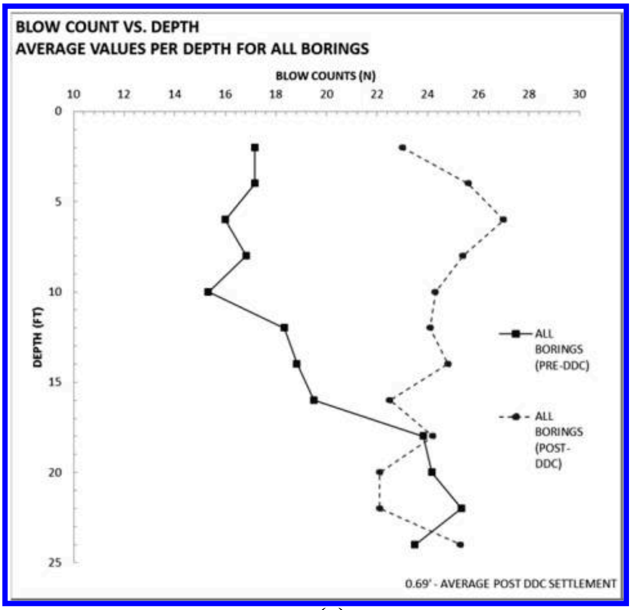
FIG. 7. DDC drop point grid pattern

(a)

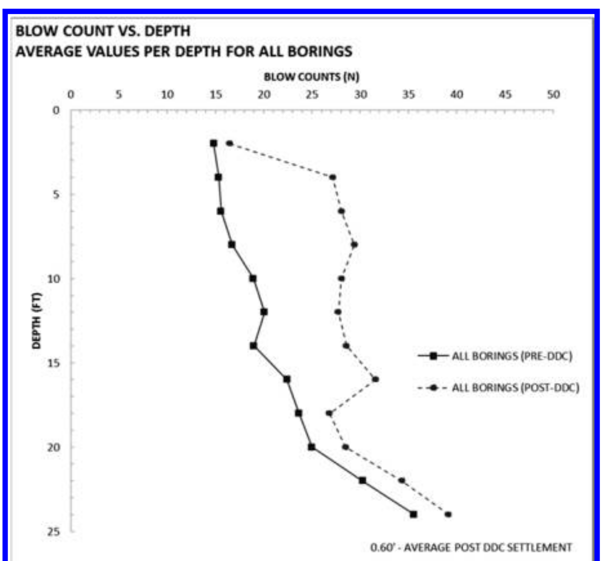


(b)

Photograph 5. Photographs of DDC at the Sediment Drying Beds: (a) Craters formed during the DDC pilot test; and (b) Aerial view of DDC craters formed during production (Source: Colorado Springs Utilities).



(a)



(b)

FIG. 8. Blow count versus depth: (a) Backwash Recovery Lagoon (b) Sediment Drying Beds